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Approved for public release; distribution is unlimited.

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14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Roberto Myers
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Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 17-Nov-2017

Agency Code:

Proposal Number: 63764EL

Agreement Number: W911NF-13-1-0329

INVESTIGATOR(S):

Name: Roberto Correa Myers
Email: myers.1079@osu.edu
Phone Number: 6142928439
Principal: Y

Organization: **Ohio State University**
Address: 1960 Kenny Road, Columbus, OH 432101016
Country: USA

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Begin Performance Period: 05-Aug-2013 **End Performance Period:** 04-Aug-2016
Report Term: 0-Other
Submitted By: Roberto Myers Email: myers.1079@osu.edu
Phone: (614) 292-8439
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 4 **STEM Participants:** 4

Major Goals: We developed a new type of pn-diode not requiring impurity doping, polarization-induced nanowire LEDs (PINLEDs) containing zero dislocations, and exhibiting hole conductivity in AlGaN without acceptor doping. Building on our development of PINLEDs, the goal of this 3 year project was to study the fundamental optical and electronic processes in PINLEDs to understand the limits of efficiency in deep UV optoelectronics based on AlGaN in the absence of dislocations and ionized impurity dopants. To study the effect of strain and confinement energy on optical properties, AlGaN and InGaN quantum disks with compositions across the entire alloy ranges were to be developed taking advantage of strain accommodation in nanowires enabling exploration of quantum disks active regions with unusually large confinement. The limits of polarization-induced conductivity were to be tested by steepening the compositional grade to boost polarization charge, as well as by examining how passivation or modulation doping affects diode conductivity. Besides ensemble measurements, individual PINLEDs were to be electrically probed using scanning conductance probe microscopy (SCPM).

Accomplishments: This 3 year project involved training of a total of four graduate students, two of which earned PhD's and two Master's degrees based in large part on this project. Of the 8 journal articles stemming directly from this project, they have been cited over 100 times.

After receiving ARO funding in August 2013, we began work to push the PINLEDs to shorter wavelengths. In 2014, we demonstrated the first ever deep UV (<270nm) wavelength nanowire LED, which is also integrated on p-type Si wafers [see slide 2]. Originally AlGaN nanowire devices exhibited a strong EL peak at 300nm, however with increased substrate growth temperatures, the 300nm peak is removed and the quantum well EL is recovered. Although the devices are currently far from optimized, the basic materials synthesis was in place.

In 2014 to 2015, we dedicated our work to optimize the performance of the nanowire LEDs grown on Si. Two methods were used to take advantage of polarization properties of III-Nitrides and improve the LED operation. In both cases, these projects were first of their kind.

We incorporated tunnel junctions inside of nanowire LEDs [see slide 3]. This allows for conversion from n-type to p-type conduction to allow for better electrical contact and therefore higher efficiency hole injection. This was the first (and currently only report) of tunnel junction incorporation into III-Nitride nanowires. The tunnel junctions lead to huge reduction in threshold voltage and therefore allow us to push much higher current through the LEDs with high power efficiency.

We carried out the first ever systematic tuning of polarization hole doping [see slide 3]. Our devices achieve high

carrier concentrations by performing concentration gradient, which leads to polarization induced conductivity. In a first ever study, we systematically varied the concentration gradient leading to measurable changes in the polarization induced hole doping. We found that by performing a very steep concentration gradient, we could reach free hole densities of more than 1E19 cm^-3 with minimal donor compensation. These results have significant repercussions not just for nanowire, but also entire Nitride community.

After demonstrating electrical optimization of the LED structures as shown in the previous slide, we focused on optimizing the active regions.

Following a prediction from NRL that Auger recombination could be reduced by altering the quantum well shape in AlGaN UV LEDs, we carried out a study to investigate the effect of quantum well shape on the EL. Our simulations show that square QWs exhibit much smaller e-h overlap than parabolic quantum wells.

To validate the simulations, nanowire LEDs were grown with square or parabolic active regions with different thicknesses. In all cases, the parabolic QWs exhibited more intense EL, which is attributable to the increased e-h overlap as well as reduced Auger recombination [see slide 4].

To our knowledge this is the first and only demonstration of enhanced EL in III-Nitride LED by using parabolic QW profile and is thus of importance to not only the nanowire, but the entire Nitride optoelectronics community.

In 2015 we also began study of active regions consisting of pure GaN but with thicknesses of just 1 to 2 ML. Such ultrathin GaN quantum disks had previously been shown in bulk to exhibit UV emission. Detailed STEM microscopy study of our samples revealed defect-free ultrathin GaN active regions with AlN barriers. We constructed LEDs from theses structures and found EL peaks down to 240nm. This is the record shortest EL wavelength ever reported for pure GaN [see slide 5]. The advantage of pure GaN vs AlGaN quantum well active regions, is that GaN may exhibit different optical selection rules to allow enhanced deep UV emission (work still in progress). Supporting this hypothesis, the ultrathin GaN LEDs exhibit 20times brighter EL than our purely AlGaN QW LEDs.

In 2015, we demonstrated operational devices on metallic thin films. This demonstrates the versatility of the synthesis allowing synthesis of these LEDs on molybdenum coated glass substrates. These are the first operational nanowire LEDs to be grown directly on metal films to our knowledge. Since our report appeared, there appears to have been a rapid increase in interest in this topic (nanowires on metal), with an additional report of operational visible wavelength InGaN nanowires grown on bulk polycrystalline Mo substrates appearing very shortly after our article appeared.

In summer 2015, we began growth of III-Nitride nanowires on metal foils to examine the possibility of scalable nanomanufacturing of III-Nitride optoelectronics. The very first PAMBE growths on as-received Ta and Ti flexible metal foils resulted in good nanowire growth. PL measurements show that the optical quality of these nanowires is as good as those of nanowires grown on single crystalline Si wafers. Finally, we grew a nanowire LED with AlGaN active region as a proof of concept. Although the early devices are dim, they actually result in measurable EL emerging from the AlGaN active regions, with peak at 350nm range. This was the first time, to our knowledge, that nanowire LED (or any LED for that matter) was directly grown on a flexible free-standing metal foil. We believe these results pave the way for scalable nanomanufacturing of III-Nitride optoelectronics (roll 2 roll for example) [see slide 6]. Since our accomplishment of operational nanowire LEDs on metal foil, a number of groups have moved forward with this approach.

Training Opportunities: Nothing to Report

Results Dissemination: 1. June 2016, Electronic Materials Conference, Newark, DE, “Integration of Ultraviolet Nanowire LEDs Directly on Flexible Metal Foil – A Route Toward Scalable Photonics” Brelon J. May, A.T.M. Golam Sarwar, Roberto C. Myers (student talk).
2. May 2016, Emerging Technologies Conference, Montreal, Canada, “Nanowire Photonics Integrated on Metal for Scalable Nanomanufacturing”, Roberto C. Myers (invited).
3. November 2015, OSU Physics Department, Columbus, OH, “Fabrication and Simulation of Waveguides for AlGaN Nanowire LEDs”, Emilio A. Codecido, ATM G. Sarwar, Brelon J. May, and Roberto C. Myers (student poster).
4. October 2015, SACNAS National Conference, Washington D.C., “Towards UV lasing: Fabrication and Simulation of Waveguides for Nanowire LEDs”, Emilio A. Codecido, ATM G. Sarwar, Brelon J. May, and Roberto C. Myers (student talk).
5. October 2015, APS Bridge Conference, Miami, FL, “Fabrication of a Cavity for Deep Ultraviolet Edge Emitting Nanowire LEDs”, Emilio A. Codecido, ATM G. Sarwar, Brelon J. May, and Roberto C. Myers (student poster).
6. October 2015, North American Molecular Beam Epitaxy Conference, Riviera Maya, Mexico, “III-N Nanowires on Metal Foils”. B. J. May, ATM Sarwar and R C. Myers (student poster).
7. July 2015, IEEE Photonics Society Summer Topics Meeting, Nassau, Bahamas, “Ultraviolet nanowire LEDs on silicon”, R. C. Myers (invited).
8. June 2015, Compound Semiconductor Week, Santa Barbara, CA, “Polarization hole engineering in deep-ultraviolet nanowire LEDs”, ATM Sarwar, Santino Carnevale, Thomas Kent, Brelon May, Fan Yang, David McComb, and Roberto Myers (Student talk).
9. June 2015, Device Research Conference, Columbus, OH, “Tunnel Junction Integrated Ultraviolet Nanowire LEDs”, ATM Golam Sarwar, Brelon May, and Roberto C. Myers (Student talk).
10. June 2015, Electronic Materials Conference, Columbus, OH, “Fabrication of a Cavity for Deep Ultraviolet Edge Emitting Nanowire LEDs”, Emilio A. Codecido, ATM G. Sarwar, Brelon J. May, and Roberto C. Myers (student talk).
11. May 2015, IMR Materials Week, Columbus, OH, “Fabrication of a Cavity for Deep Ultraviolet Edge Emitting Nanowire LEDs”, Emilio A. Codecido, ATM G. Sarwar, Brelon J. May, and Roberto C. Myers (student poster).
12. February 2015, SPIE Photonics West, San Francisco, California, “Tunnel-junction-enhanced ultraviolet nanowire light-emitting diodes integrated on silicon”, A. T. M. G. Sarwar, B. J. May, and R. C. Myers (student talk).
13. June 2014, Electronic Materials Conference, Santa Barbara, California, “Tunable Deep Ultraviolet Electroluminescence from Nanowire Light Emitting Diodes with AlxGa1-xN Active Regions”. T. F. Kent, S. D. Carnevale, A. T. M. G. Sarwar, and R. C. Myers (student talk).
14. June 2014, Electronic Materials Conference, Santa Barbara, California, “Engineering the polarization hole doping of graded nanowire ultraviolet LEDs integrated on Molybdenum and Silicon”. A. T. M. G. Sarwar, S. D. Carnevale, T. F. Kent and R. C. Myers (student talk).
15. May 2014, IMR Materials Week, Columbus, Ohio, “Polarization-induced UV nanowire LEDs on silicon and molybdenum films”. A. T. M. G. Sarwar, S. D. Carnevale, T. F. Kent, F. Yang, R. C. Myers (student poster).
16. May 2014, IMR Materials Week, Columbus, Ohio, “Tunable Deep Ultraviolet Electroluminescence from Nanowire Light Emitting Diodes with AlxGa1-xN Active Regions”. T. F. Kent, S. D. Carnevale, A. T. M. G. Sarwar, and R. C. Myers (student poster).
17. February 2014, SPIE Photonics West, San Francisco, California, “Polarization-Induced Nanowire Light Emitting Diodes with Deep Ultraviolet Emission”, T. F. Kent, S. D. Carnevale, A. T. M. G. Sarwar, and R. C. Myers (student talk).
18. February 2014, Lawrence Symposium on Epitaxy, Scottsdale AZ, “Wide bandgap heterostructures, tunnel junctions and nanowires”, R. C. Myers (invited).
19. August 2013, International Conference on Nitride Semiconductors, Washington, D.C., “Ferromagnetism and magneto-transport in Gd-doped AlN-GaN two-dimensional electron gases”, Z. Yang, T. F. Kent, H. Jin, J. Yang, and R. C. Myers (student talk).
20. August 2013, International Conference on Nitride Semiconductors, Washington, D.C., “Atomically Sharp 318nm Gd:AlGaN Ultraviolet Light Emitting Diodes on Si with Low Threshold Voltage”, Thomas F. Kent, Santino D. Carnevale, and Roberto C. Myers (student poster).

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

RPPR Final Report
as of 17-Nov-2017

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: ATM Golam Sarwar
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Thomas Kent
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Brelon May
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Emilio Codecido
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: PD/PI
Participant: Roberto Myers
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2015 73rd Annual Device Research Conference (DRC)
Date Received: 07-Sep-2017 Conference Date: 21-Jun-2015 Date Published: 06-Aug-2015
Conference Location: Columbus, OH, USA
Paper Title: Tunnel junction integrated ultraviolet nanowire LEDs
Authors: ATM Golam Sarwar, Brelon J May, R. C. Myers
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: The Ohio State University
Date Received: 07-Sep-2017 Completion Date: 8/8/14 6:56PM
Title: III-Nitride Nanostructures for Optoelectronic and Magnetic Functionalities: Growth, Characterization and Engineering
Authors: Thomas F. Kent
Acknowledged Federal Support: **N**

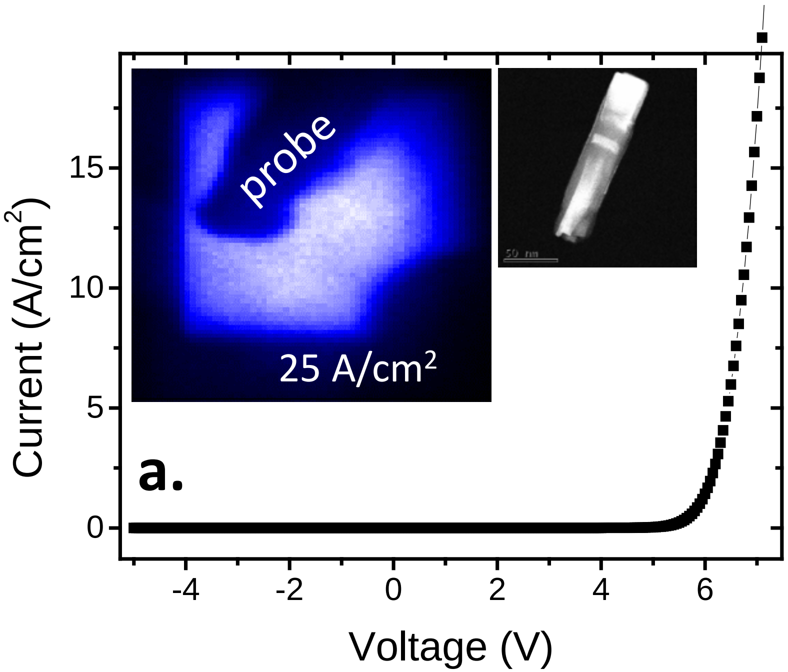
Publication Type: Thesis or Dissertation
Institution: The Ohio State University
Date Received: 12-Sep-2017 Completion Date: 12/10/15 2:39PM
Title: Extreme Band Engineering of III-Nitride Nanowire Heterostructures for Electronic and Photonic Application
Authors: ATM Golam Sarwar
Acknowledged Federal Support: **N**

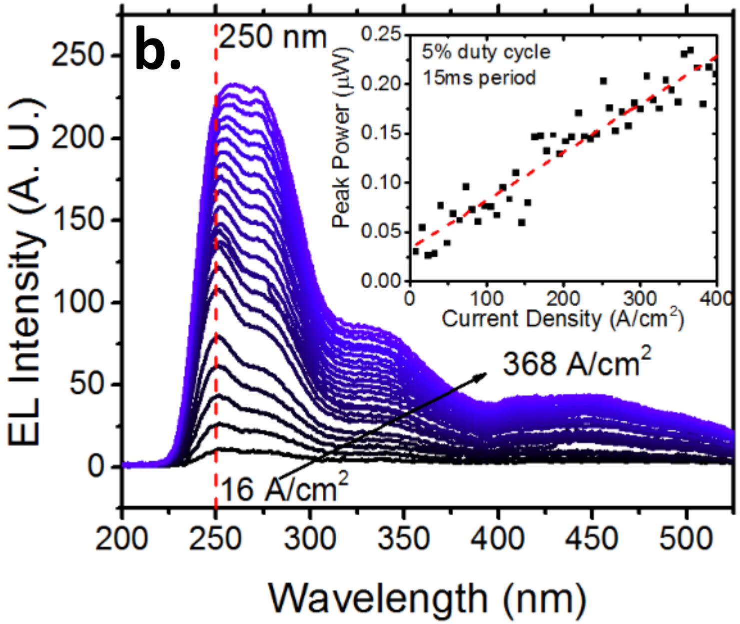
ARO final report slides

W911NF1310329

Table of Contents

2014, First deep UV nanowire LED (<270nm)





<u>Plasma-Assisted Molecular Beam Epitaxy (PAMBE)</u>

- Polarization-induced nanowire pn-junction (back and forth, GaN→AlN→GaN composition gradient)
- High temperature grown high Al content AlGaN quantum well active region

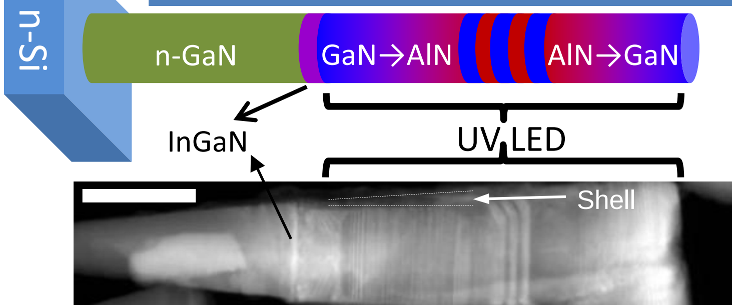
- EL emission to 250 nm
- Top emission through metal contacts,
- back contact is p-Si wafer (silicon integrated)

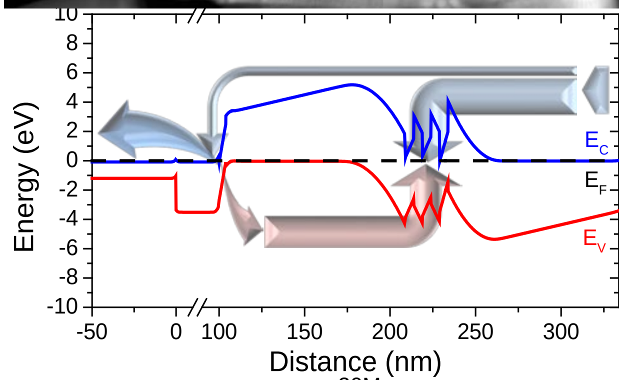
Kent et al. *Nanotechnology 25, 455201 (2014)*

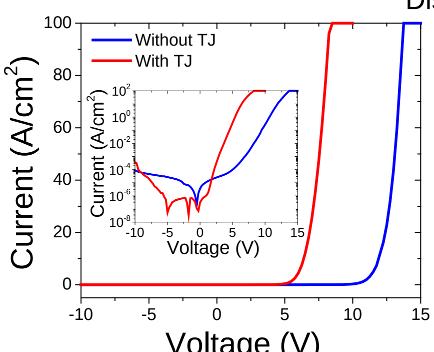
2015, Polarization-engineered nanowire LEDs

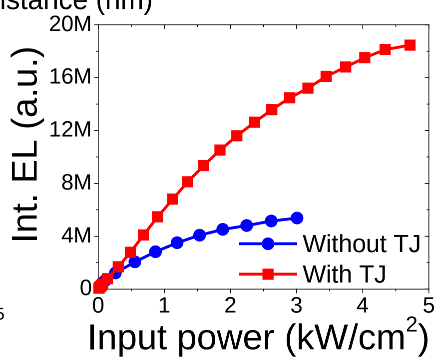
First tunnel junction enhanced nanowire LEDs by polarization engineering

Sarwar et al. *Appl. Phys. Lett. 107, 101103 (2015)*

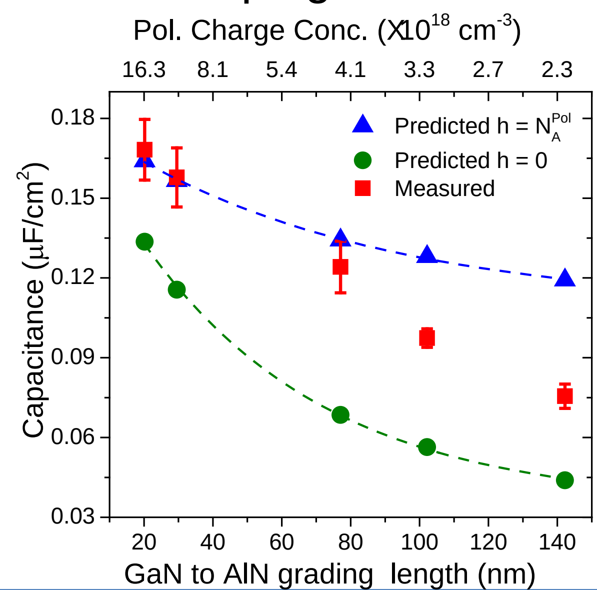




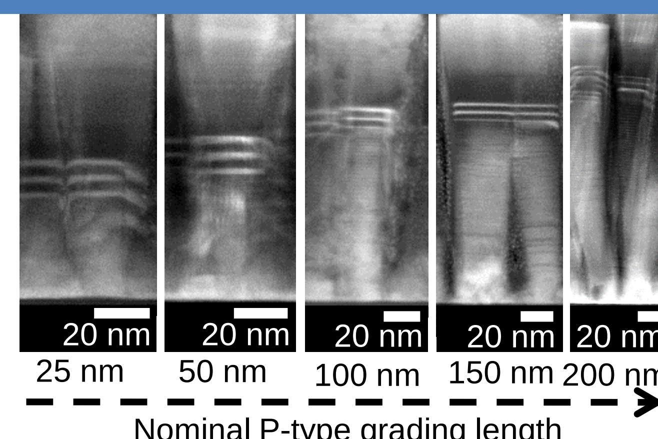




First systematic tuning of polarization hole doping in AlGaN

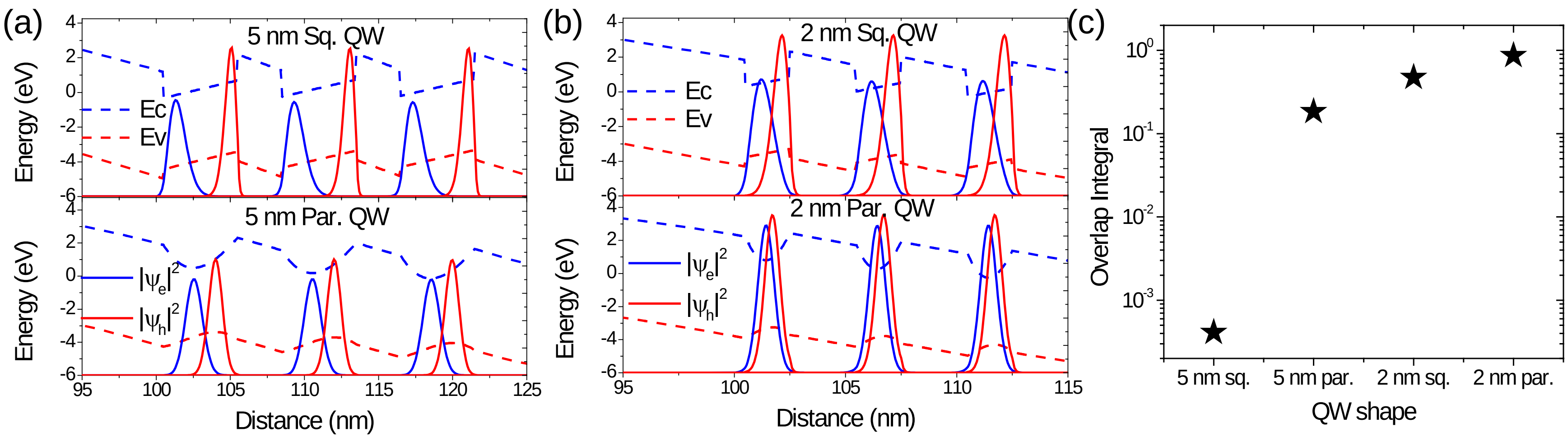


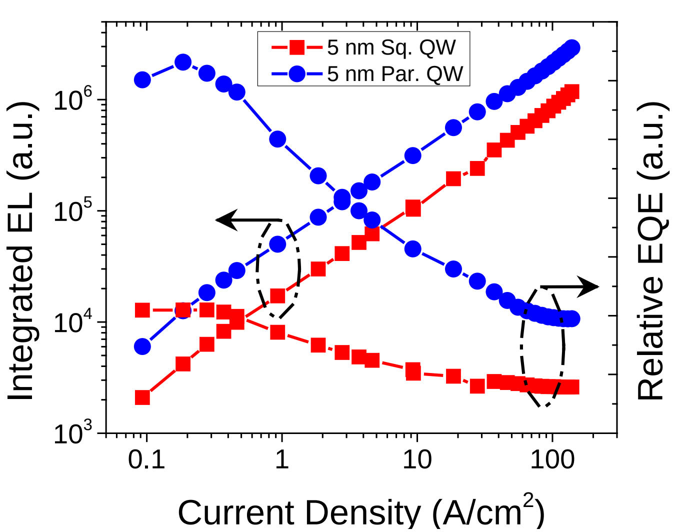
Sarwar et al. *Appl. Phys. Lett. 106, 032102 (2015)*

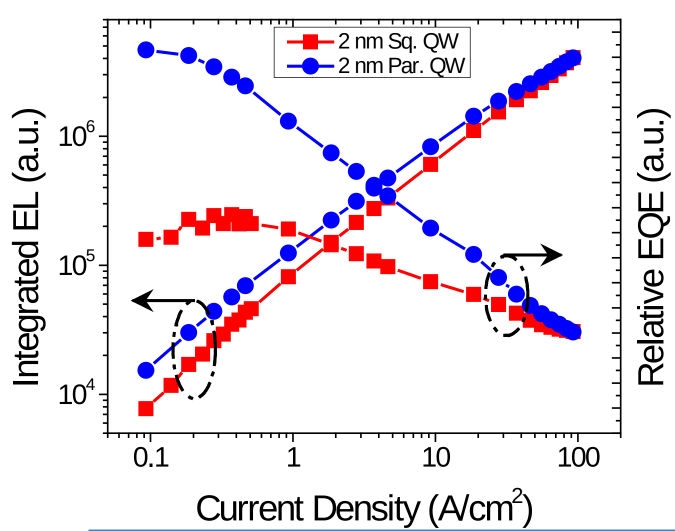


2015, Effect of quantum well shape and width

Square versus parabolic quantum wells





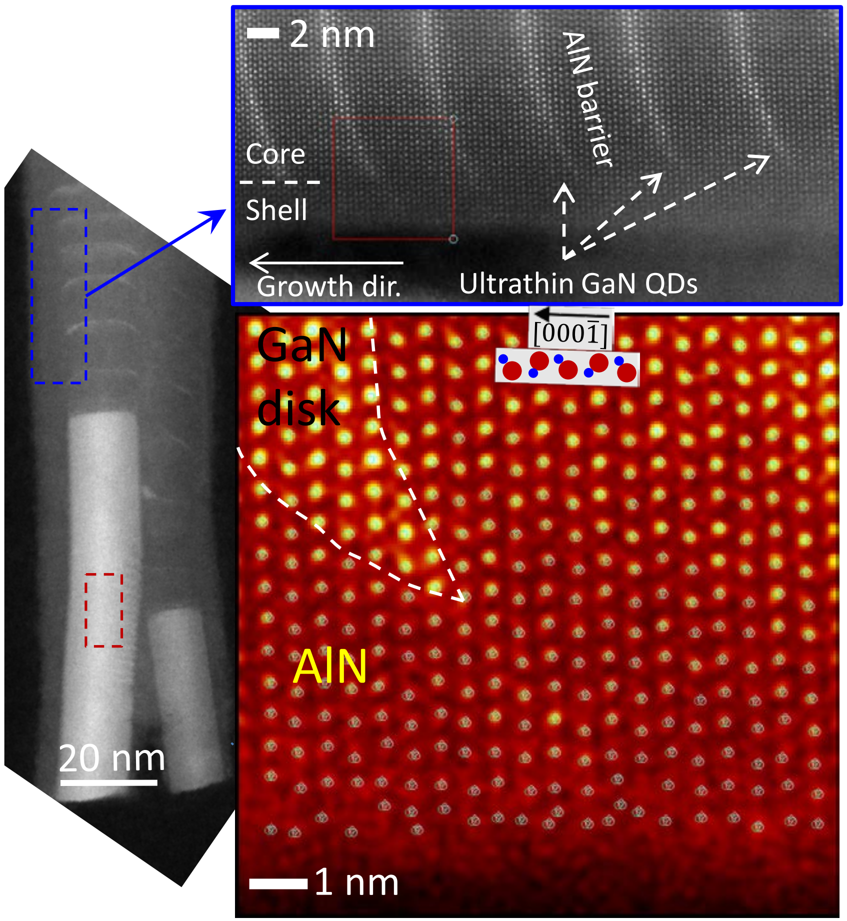


Synthesized by PAMBE

Sarwar et al. Phys. Status Solidi A. *(2015)*

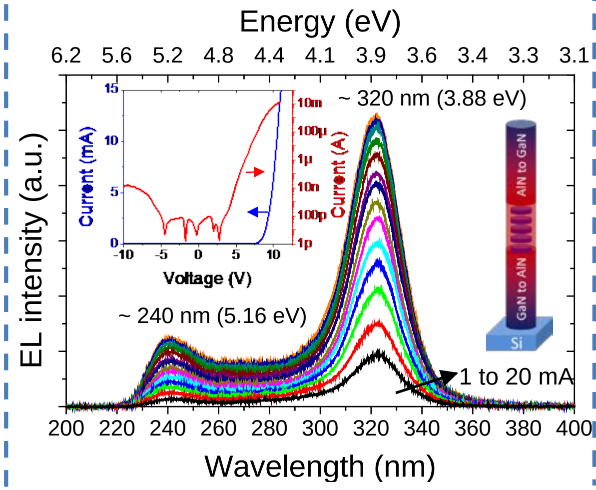
2016, Deep UV nanowire LEDs by extreme confinement

Ultrathin (1 to 2 ML) GaN quantum disks with AlN barriers

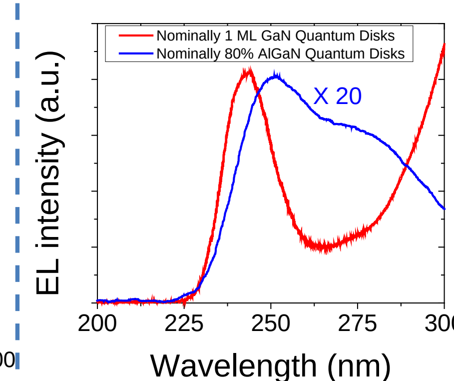


Sarwar et al. *in-review (2016)*

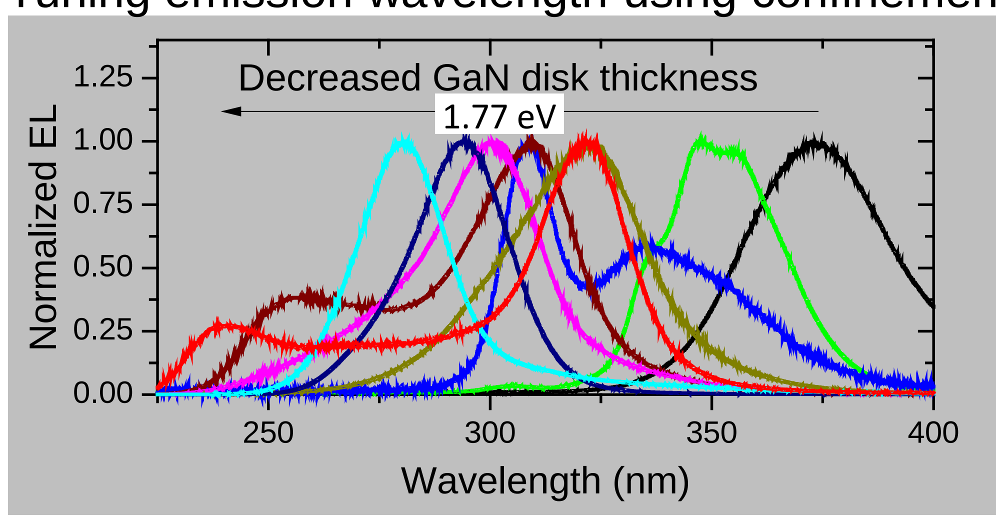
EL as short as 240nm from quantum confined GaN



Enhanced emission from GaN QDs



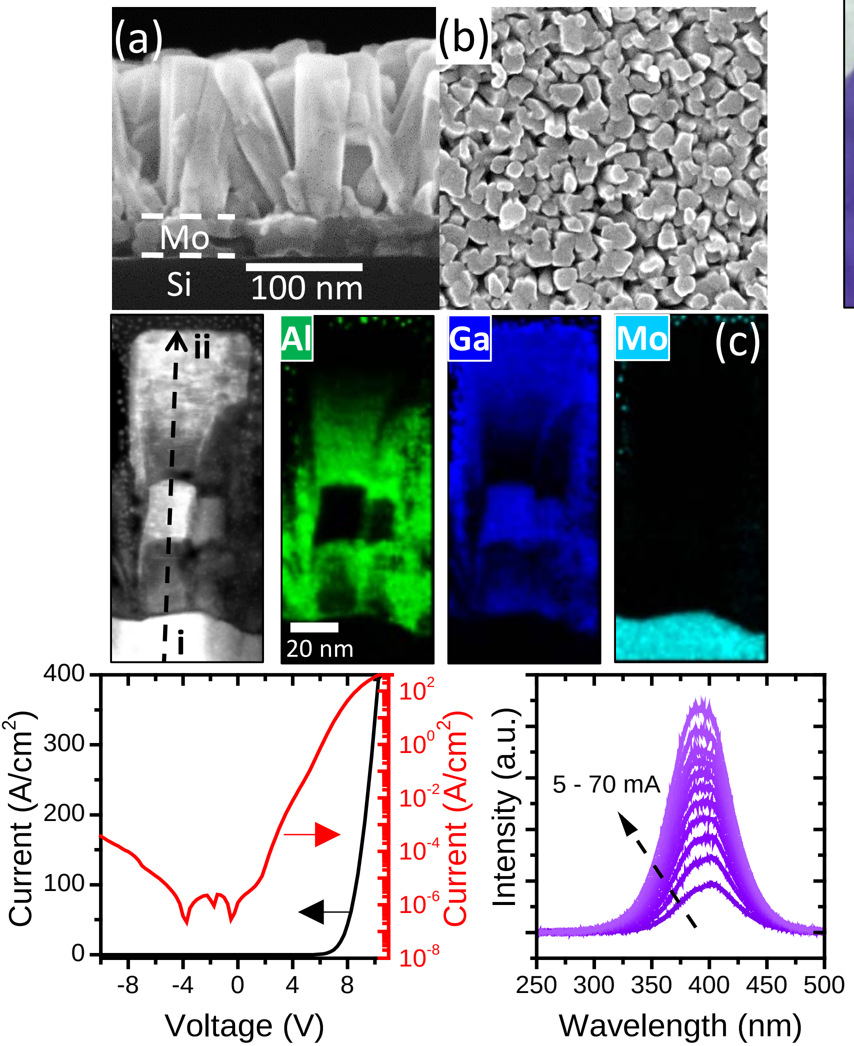
Tuning emission wavelength using confinement

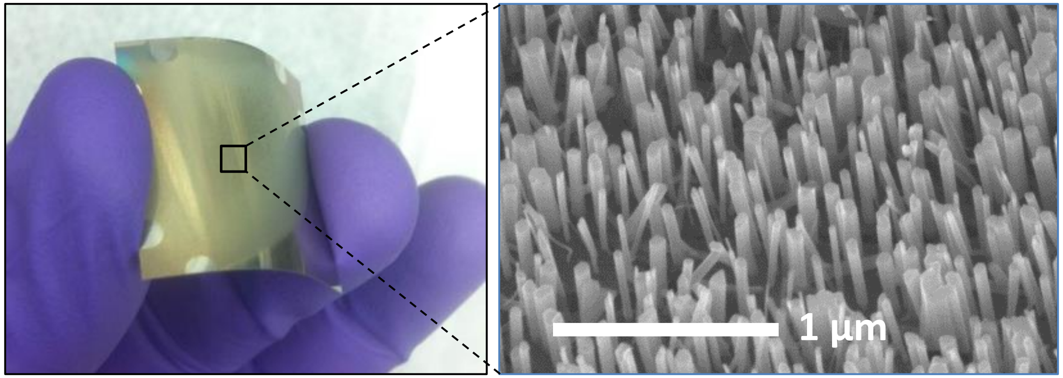


2015, First UV nanowire LEDs grown on metal

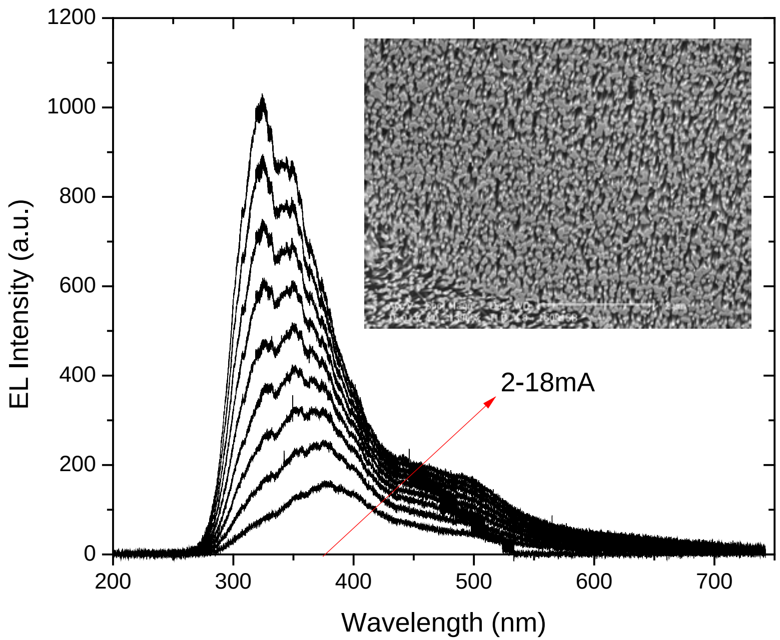
Nanowire LEDs on metal thin films → on metal foil!

Sarwar et al. *Small 11, 5402 (2015)*





May et al. *APL* 108, 141103 (2016)



THE OHIO STATE UNIVERSITY MSE Materials Science and Engineering

Deep Ultraviolet Emitting Polarization Induced Nanowire Light Emitting Diodes with $Al_xGa_{1-x}N$ Active Regions

<u>T. F. Kent</u>[1], S. D. Carnevale[2] , A. T. M. Sarwar[2], F. Yang[1], D. McComb[1] and R. C. Myers[1,2]

[1]Department of Materials and Science Engineering, Ohio State University

[2]Department of Electrical and Computer Engineering, Ohio State University

Outline –

- Prospects for solid state deep ultraviolet optoelectronics
- Polarization doping for enhanced p-type AlGaN performance
- III-nitride nanowire polarization enhanced LEDs with bandgap tunable EL
- Difficulties with high Al composition AlGaN active regions
- Utilizing high substrate temperatures to grow high quality AlGaN QWs

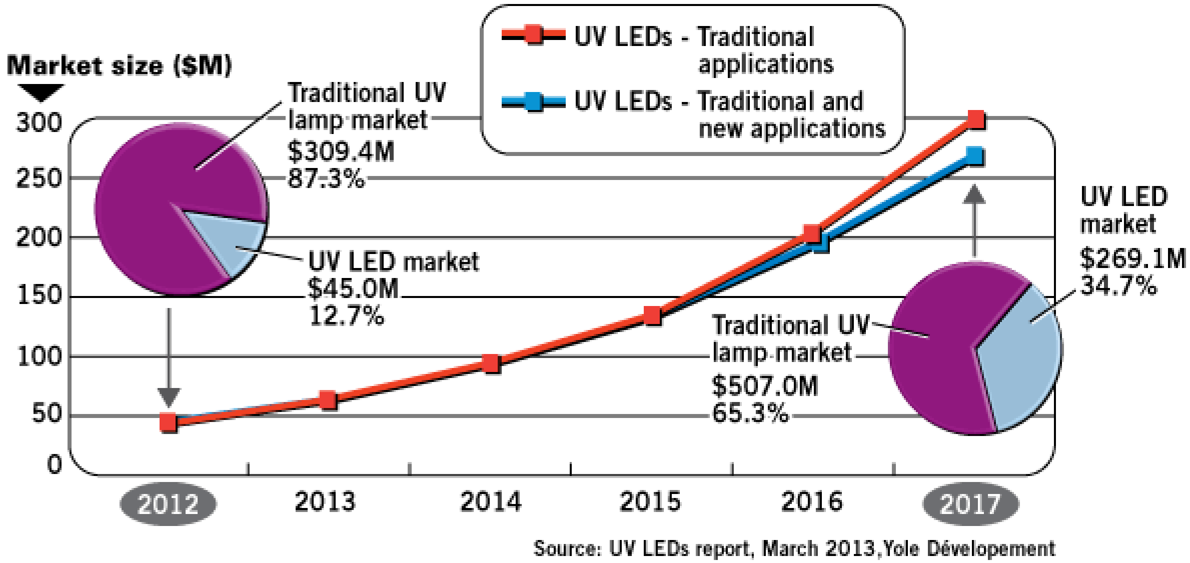
<u>For Additional Details:</u>

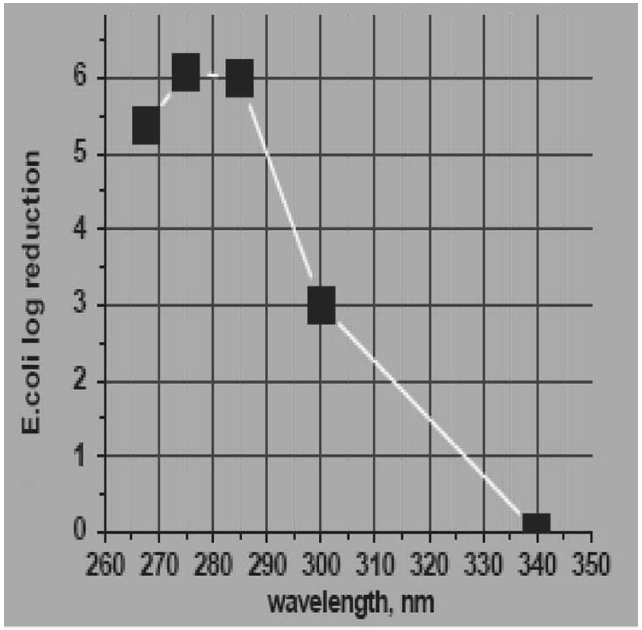
S. D. Carnevale, T. F. Kent, *et al.*, *Nano Lett.*, **2012**, *12* (2), pp 915–920

S. D. Carnevale, T. F. Kent, *et al.*, *Nano Lett.*, **2013**, *13* (7), pp 3029–3035

T. F. Kent, S. D. Carnevale and R. C. Myers, Appl. Phys. Lett. **102**, 201114 (2013)

Solid State Deep Ultraviolet Optoelectronics





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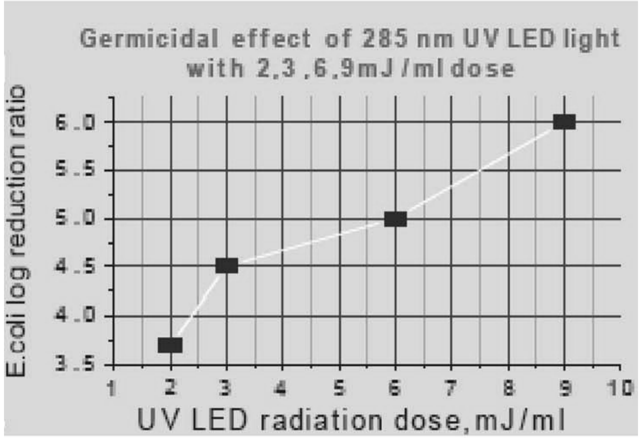


- UVB/UVC solid state emitters is a rapidly growing market
  - UV curing of adhesives
  - Water disinfection
  - Chemical Agent detection

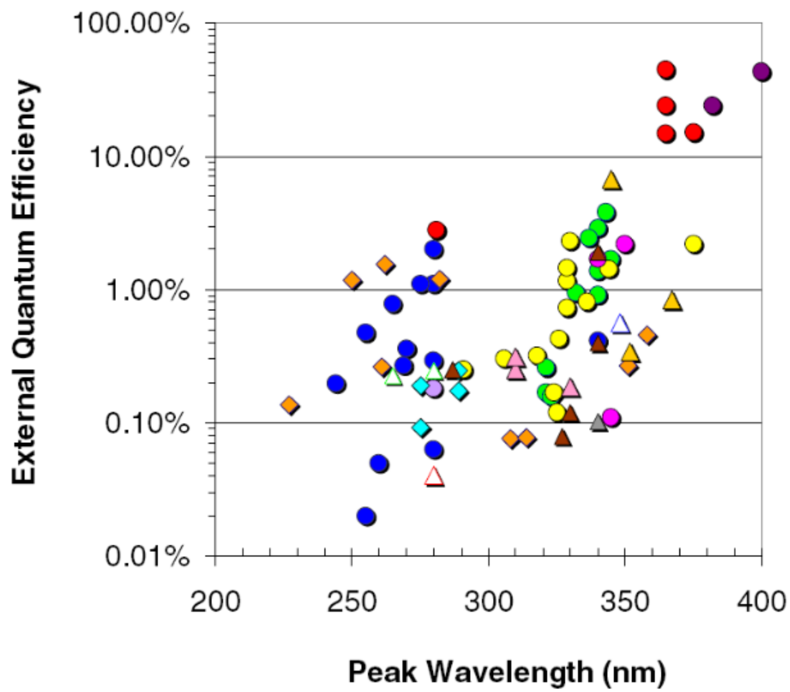
- Replacement of bulky, toxic Hg arc lamps

- Applications require high output power, EQE

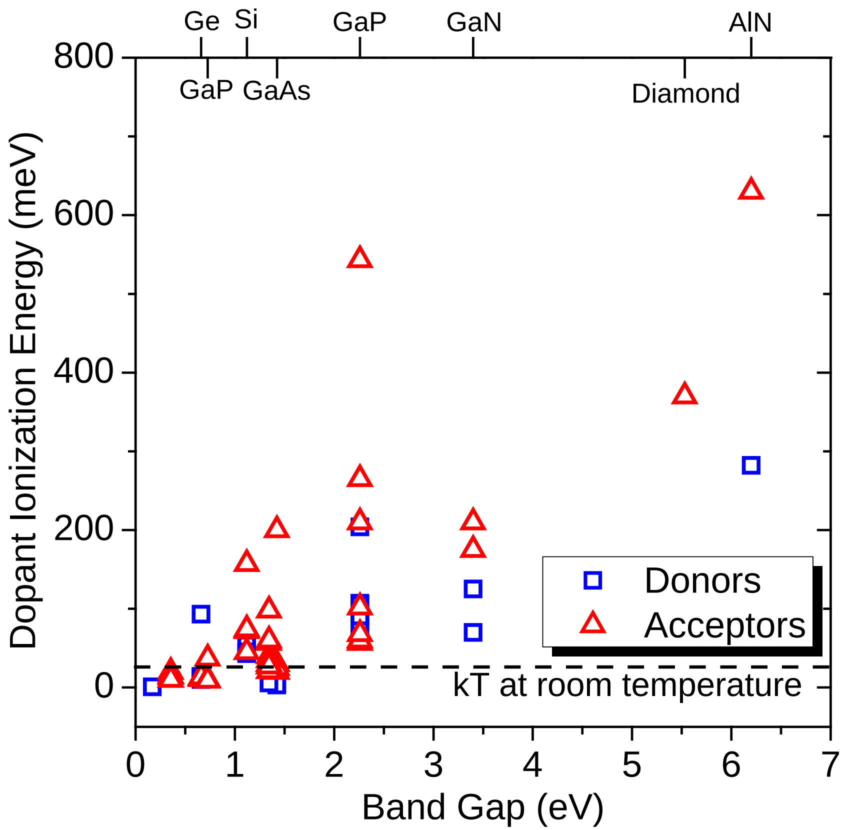
SHUR AND GASKA IEEE TRANS. ON ELEC. DEV., VOL. 57, NO. 1, 2010

What’s limiting SS-DUV technology?

- Solid state DUV emitters typical exhibit lower EQE as bandgap increases
  - poor dopant activation
  - strain driven TM/TE mode switching
  - high TDD



Kneissl et al., 2011, *Semicond. Sci. Technol.*

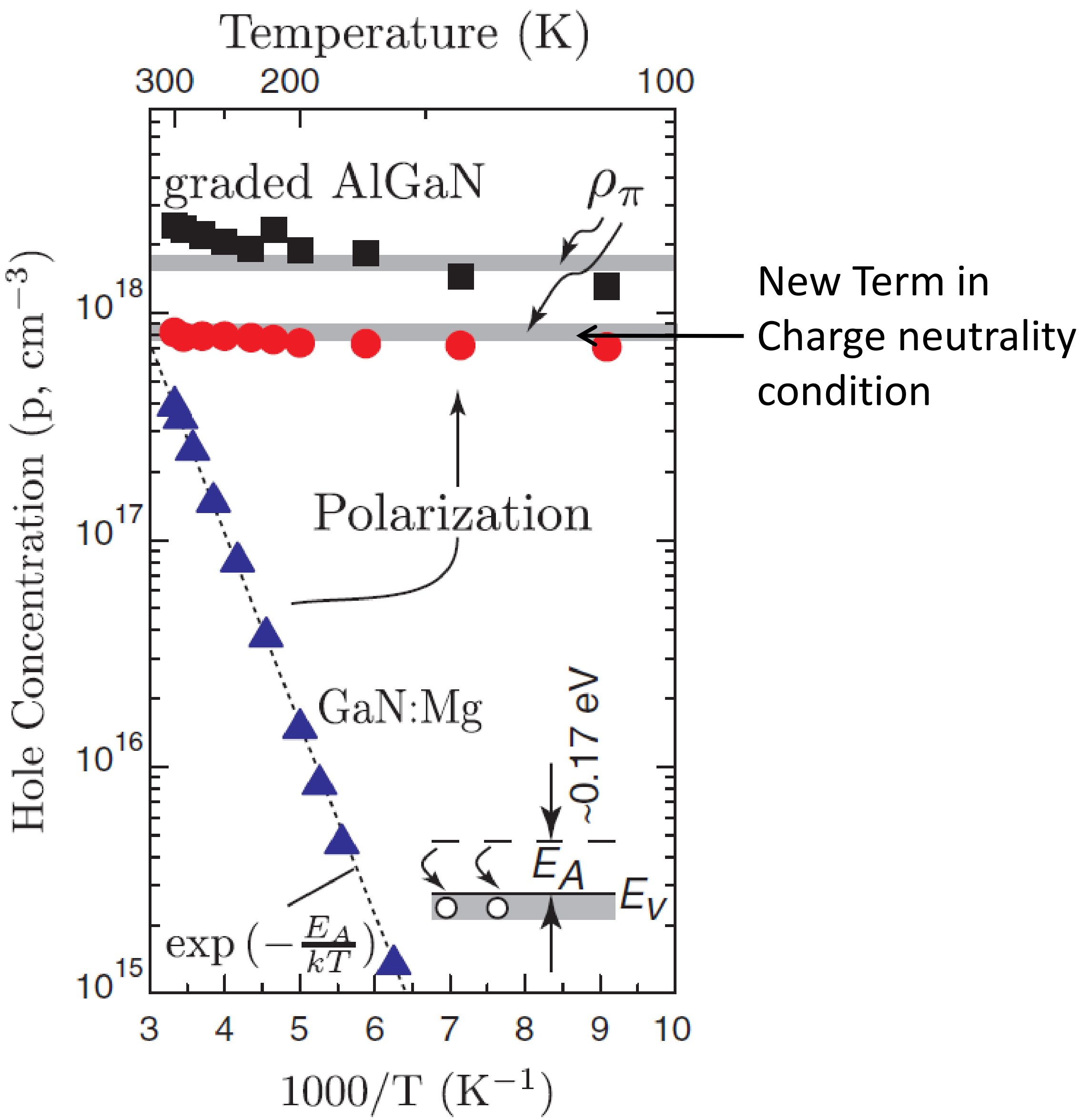


Values from: http://www.ioffe.ru/SVA/NSM/, Taniyasu et al., 2006, Nature

- Wide bandgap materials typically exhibit very large dopant activation energies
  - Can be far in excess of thermal energy

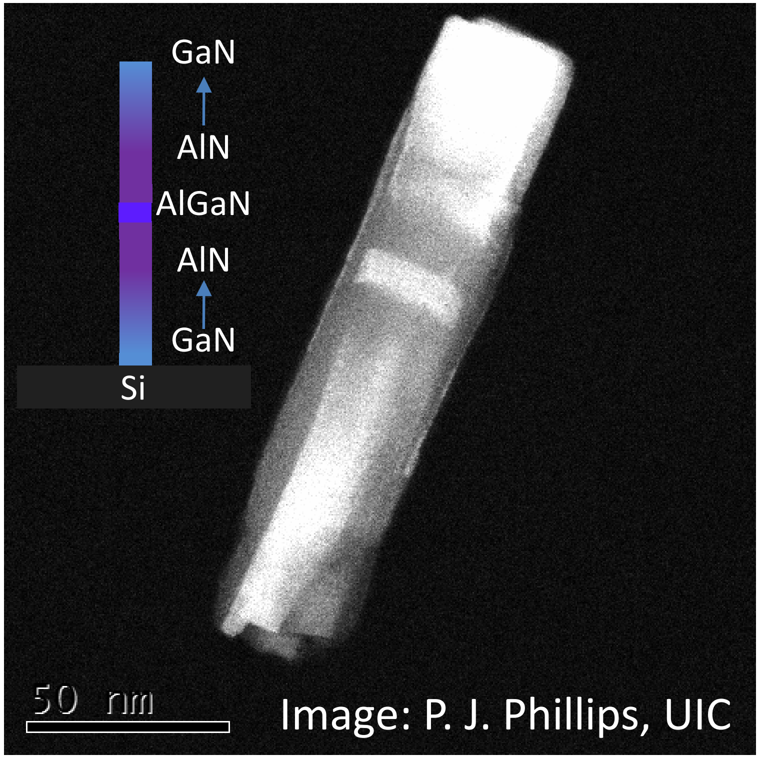
Basics of Polarization Doping in Graded III-nitrides

- III-nitride unit cells have a sizeable, composition dependent polarization moment
- Linearly grading composition in AlGaN gives rise to regions of bound charge
- Can reverse charge sign by grading from AlN to GaN
- Gives rise to additional driving force for dopant activation



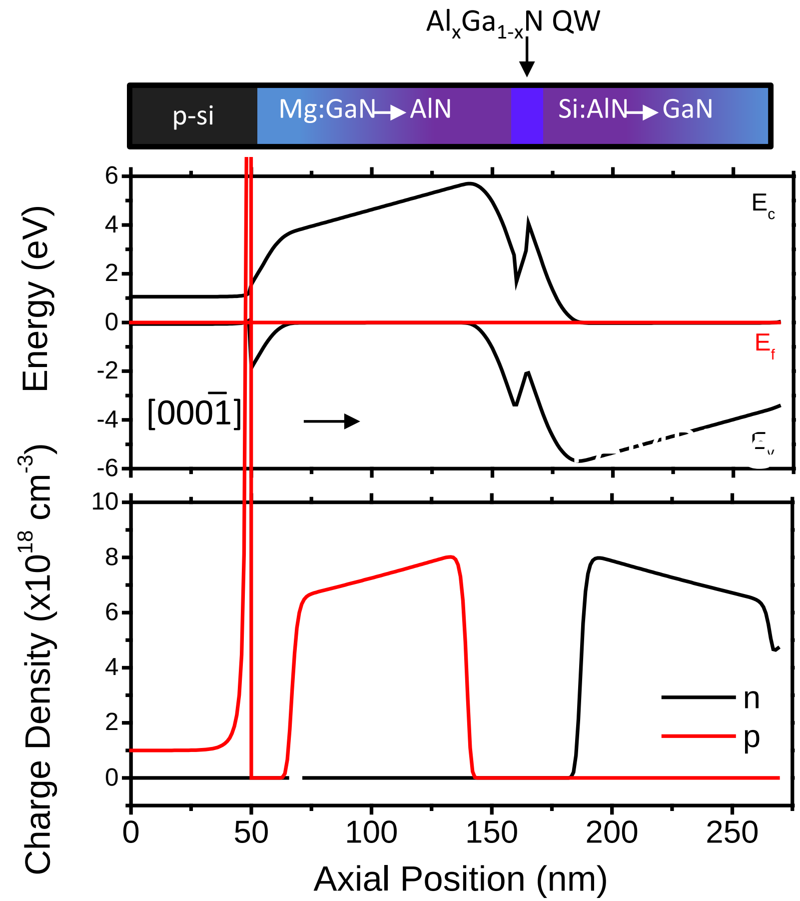
Simon et al., 2010, *Science*

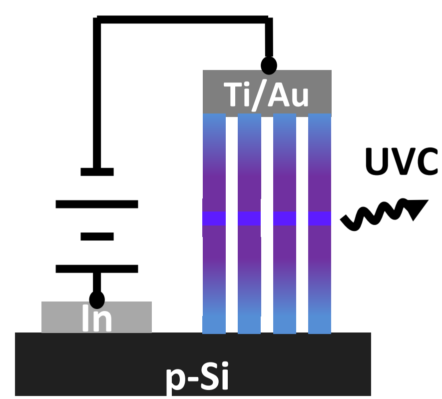
Polarization Induced Nanowire Light Emitting Diodes (PINLEDs)



- Unique strain tolerant properties of self assembled nanowires allow composition grading over the full compositional range of AlGaN

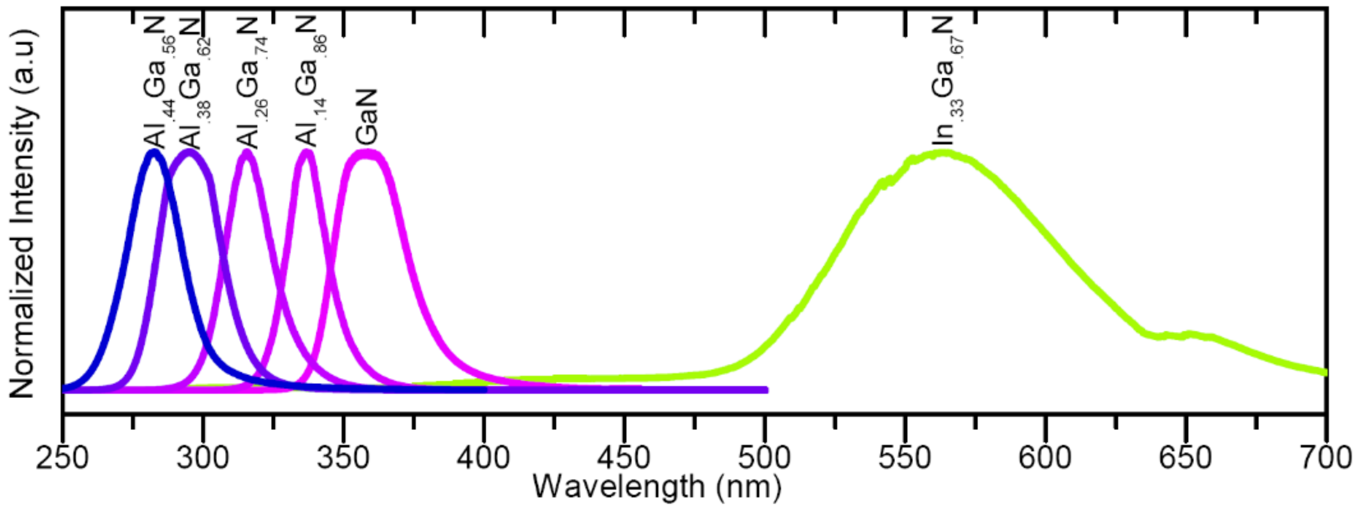
- Can form highly conductive polarization enhanced n and p-type regions of a wide bandgap pn heterojunction to make LEDs





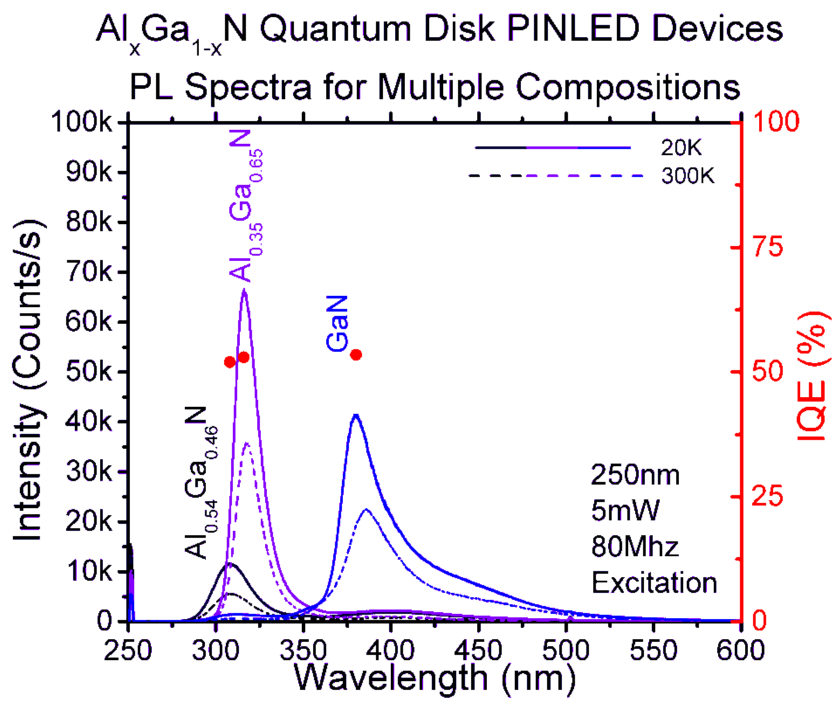
Optical Properties of PINLEDs

Electroluminescence spectra for a variety of active regions



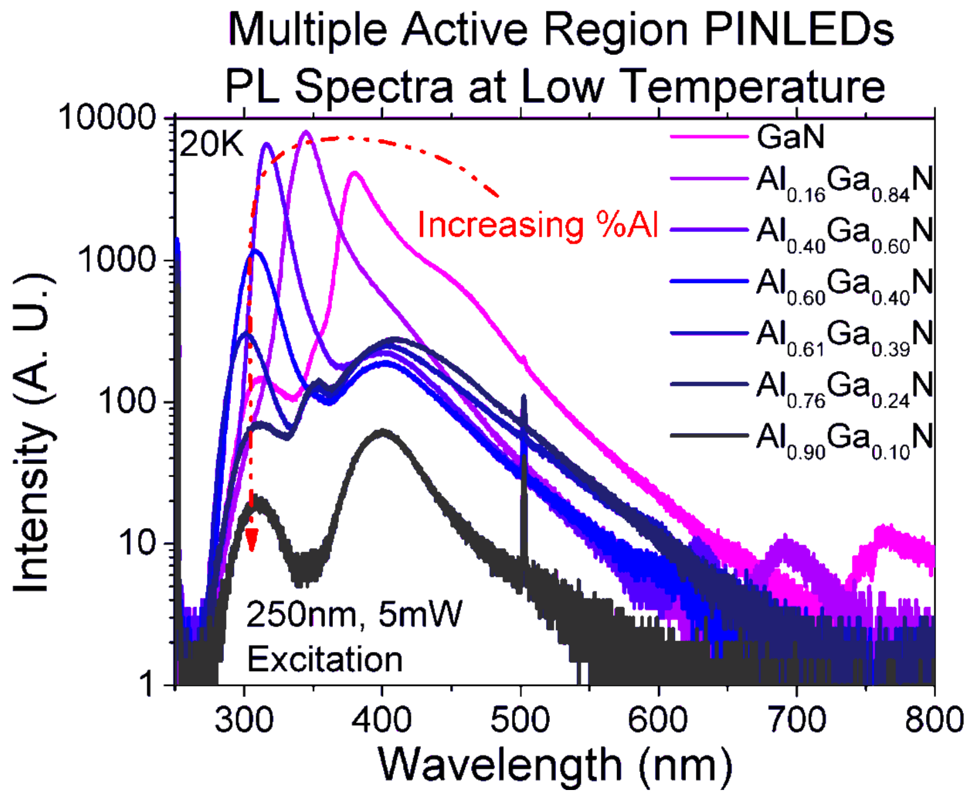
- Unique heterostucture design imparts large flexibility in active region composition/ emission wavelength

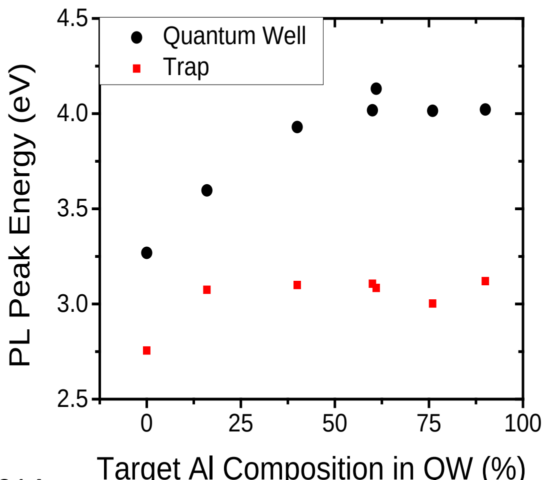
- Nanowire devices exhibit high IQE values across the composition range, suggesting that material optical quality is high

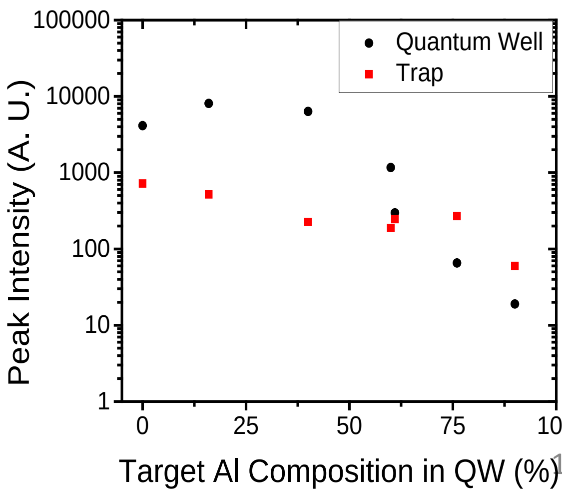


Limitations on DUV wavelength tuning

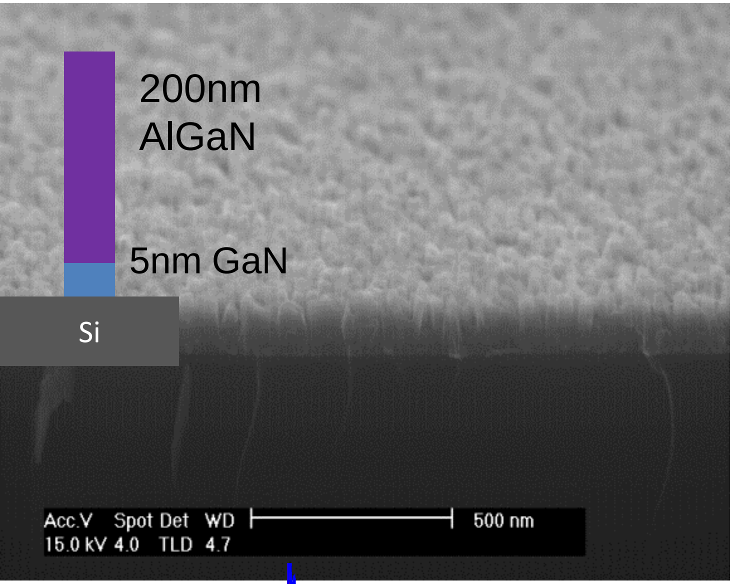
- Full spectroscopic analysis across AlGaN composition range reveals more complicated behavior
- Initially, as %Al increases, emission intensity is relatively constant and energy shifts monotonically
- As %Al exceeds 50%, peak intensity becomes quenched and emission wavelength becomes constant
- Likely due to trap in AlGaN active region, possibly oxygen related

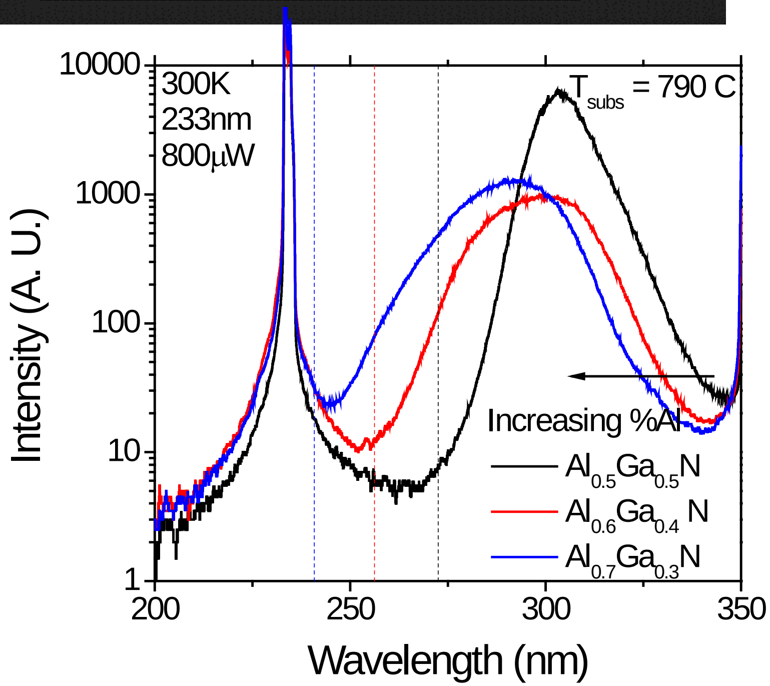






Isolation of active region material from device heterostructure





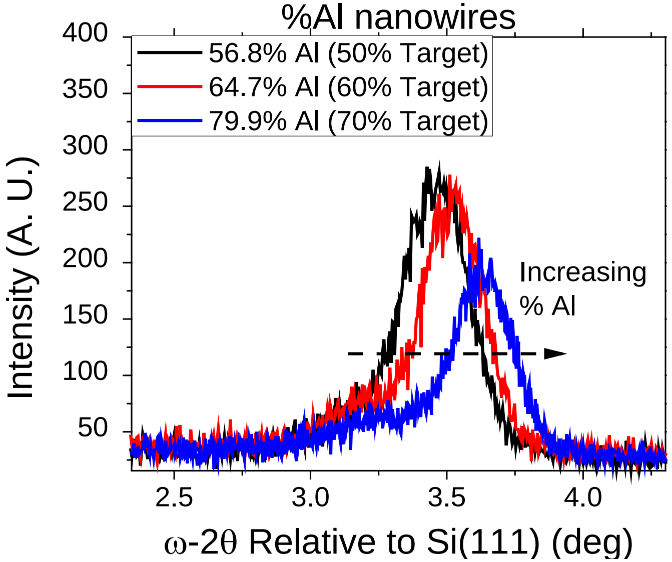
- Need to study active region optical properties independent of heterostructure

- Two step- GaN/AlGaN "bulk" structures

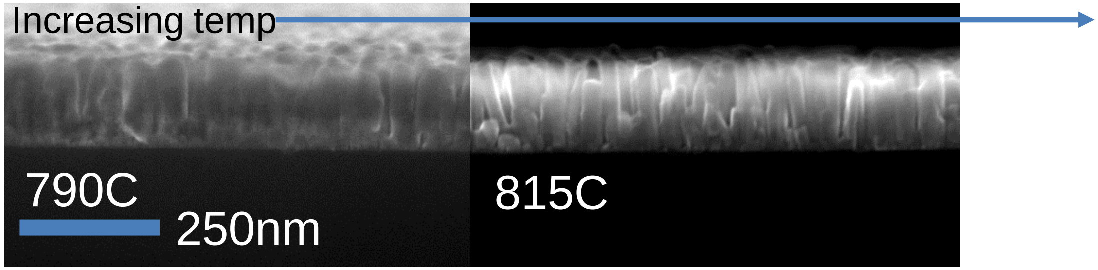
- As %Al increases, peaks become broader, but are largely centered around 300nm indicative of defect level to band edge transition

- Experimentally measured energies do not correspond with expected values for planar AlGaN films

XRD spectra of various %Al nanowires



Suppression of defect peak with increasing growth temperature

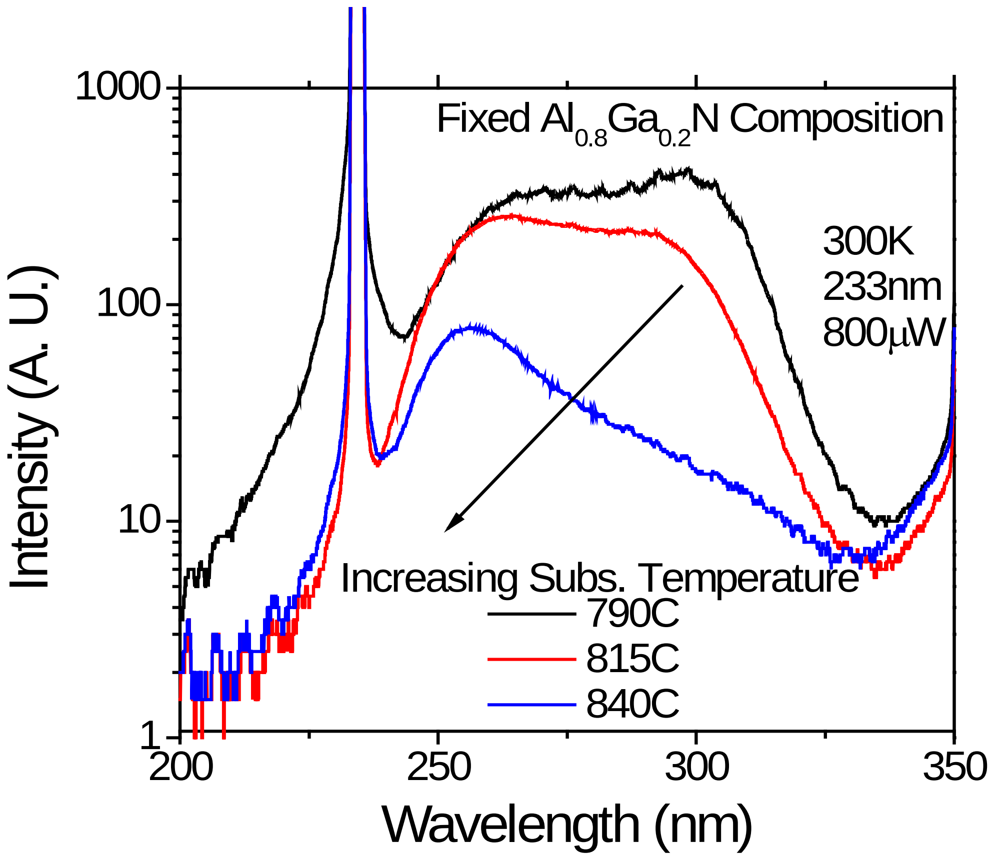


- High quality AlN is typically grown at high temperatures to overcome the low mobility of Al and reduce impurity incorporation

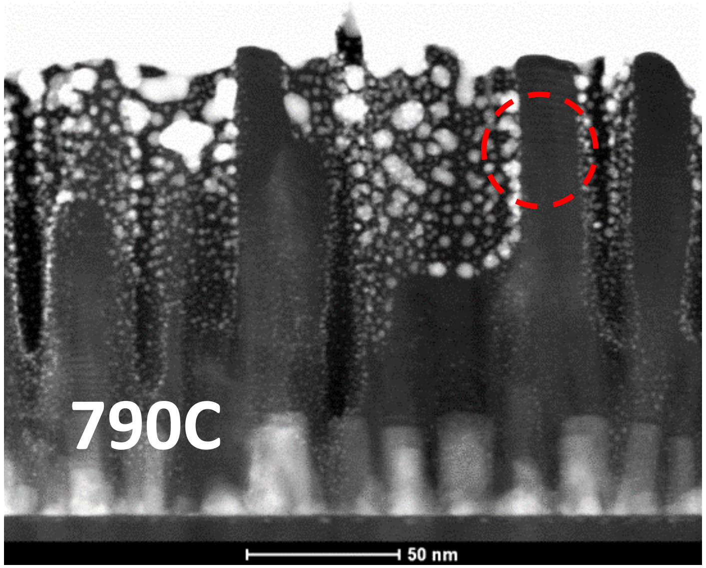
- Multiple samples at fixed composition are prepared with increasing substrate temperatures

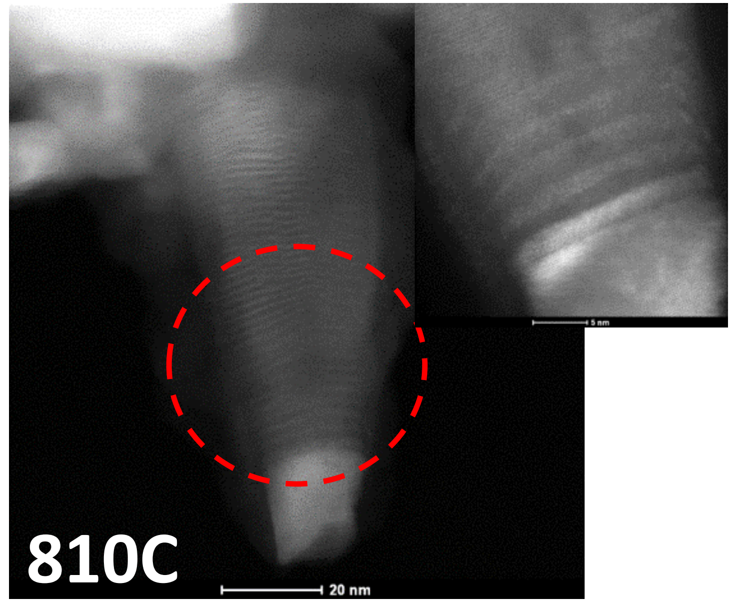
- As substrate temperature is increased, high energy emission becomes dominant

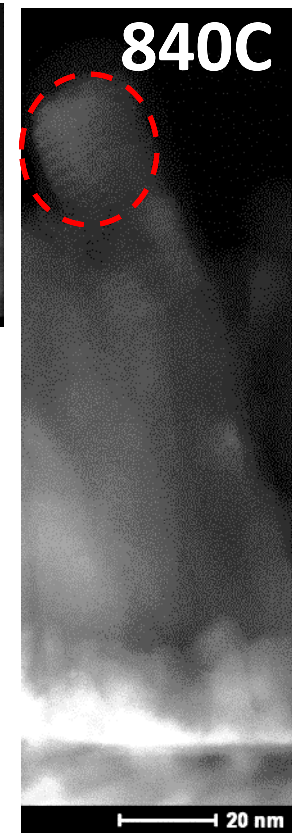
- This suggests that defect peak at 300nm can be suppressed by using high growth temperatures



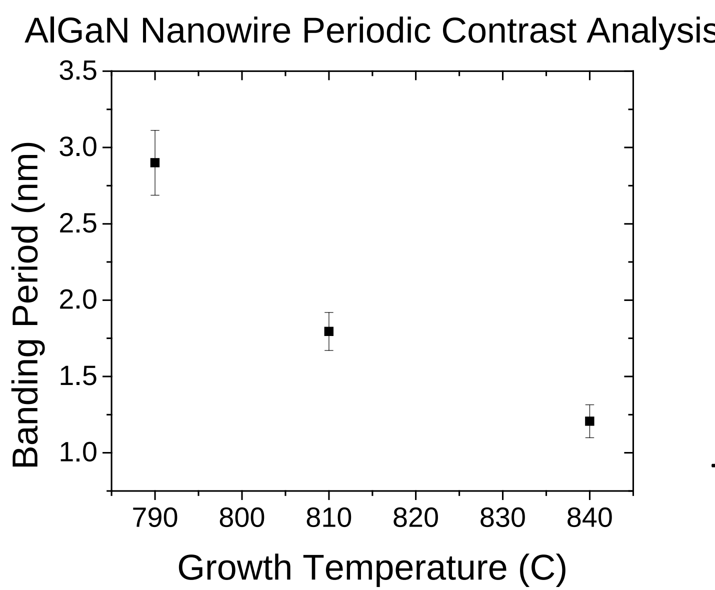
Evidence for spontaneous Alloy ordering in AlGaN Nanowires





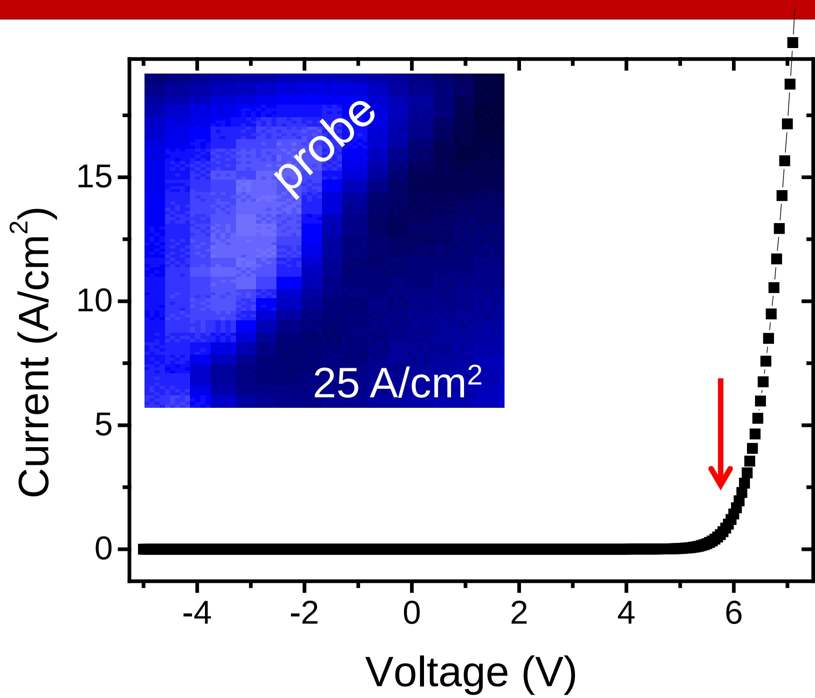


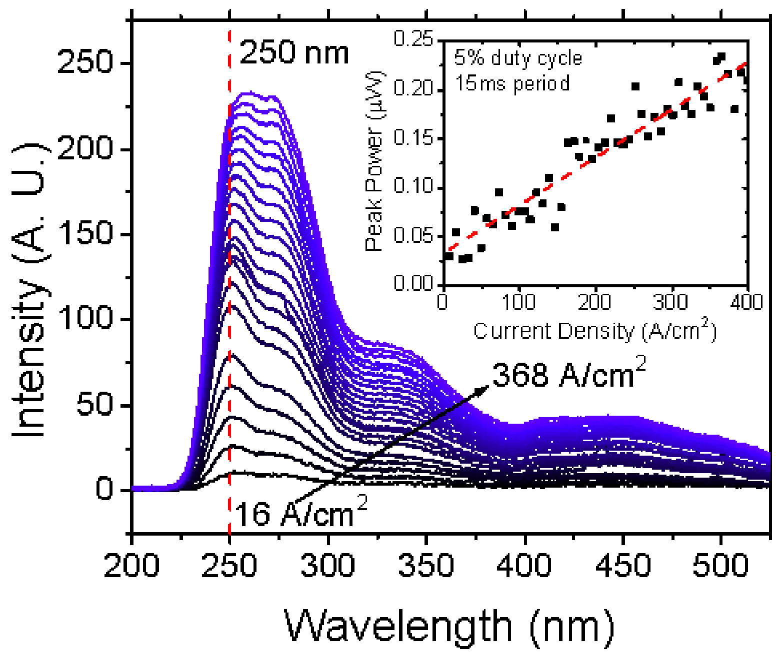
- All three samples exhibit "banding" contrast pattern.
- Period of bands monotonically decrease with temperature
- Possible evidence for spontaneous ordering in AlGaN Nanowires



T. F. Kent, F. Yang, D. McComb, R. C. Myers

Deep ultraviolet emission from high temperature active regions





- Device was prepared with high temperature growth conditions (840C) for the device quantum wells
- I-V characteristics show rectification and 6 eV turn on as expected from band diagram

- Electroluminescence spectra show peak emission at 250 nm
- Emission initially scales linearly with current density
- At higher current densities overshoot peak grows
  - 90 nW (1E-6% EQE) (DC)
  - 0.22 μW (Pulsed)

Summary and Conclusions

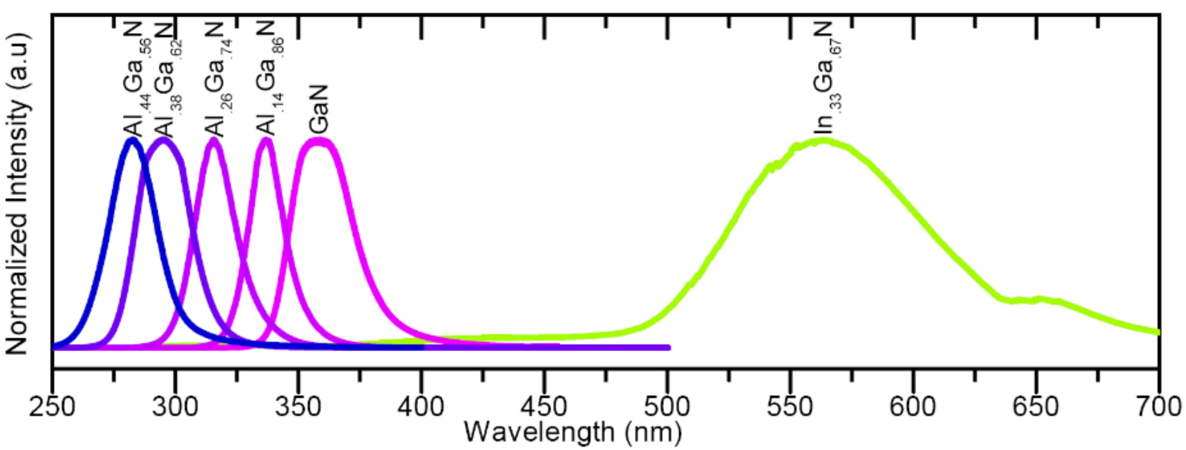
- Polarization enhanced doping can be used to enhance solid state DUV optoelectonics performance

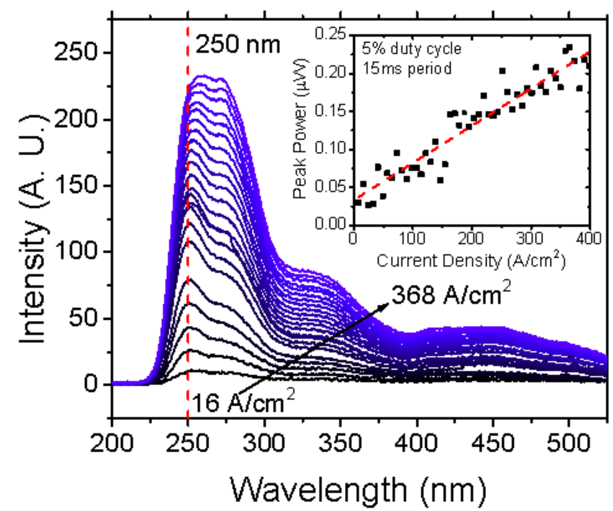
- Self assembled nanowire polarization induced nanowire LEDs possess unique properties suited towards polarization enhanced DUV emitters

- Growth of high optical quality AlGaN active regions requires higher growth temperatures than typically used for NW growth

- 250nm electroluminescence from a nanowire device

Funding Provided By:





Tunnel Junction Integrated Ultraviolet Nanowire LEDs

A. T. M. Golam Sarwar[1], Brelon May[2], and Roberto C. Myers[1,2]

[1]Department of Electrical and Computer Engineering, The Ohio State University
[2]Department of Materials Science and Engineering, The Ohio State University

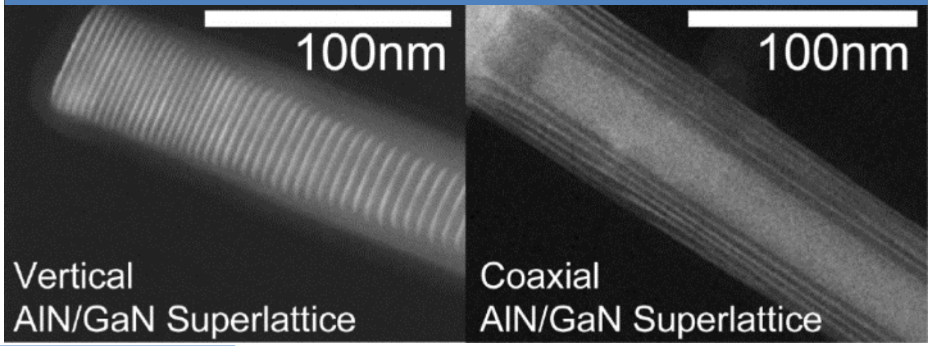
Outline:

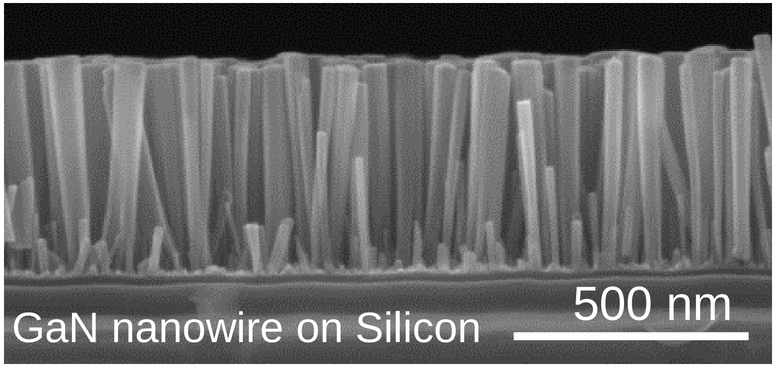
1. Polarization doping in N-face NWs
2. Why tunnel junction (TJ) is relevant.
3. III-N tunnel junctions
4. TJ integrated NW UVLED

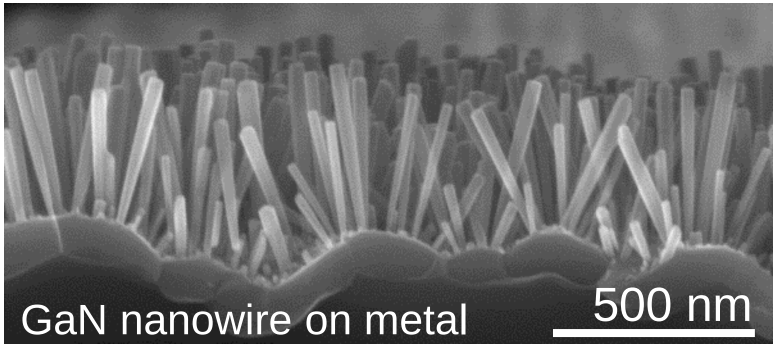
Nanowires

- Wide range of substrate
- Superior material quality
- Novel structures
- Accommodation of strain

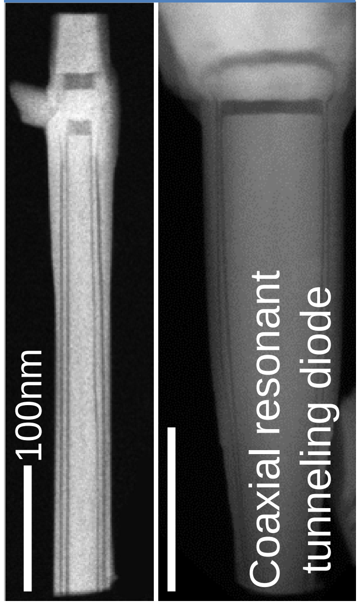
Carnevale et al, Nano Letters 2011



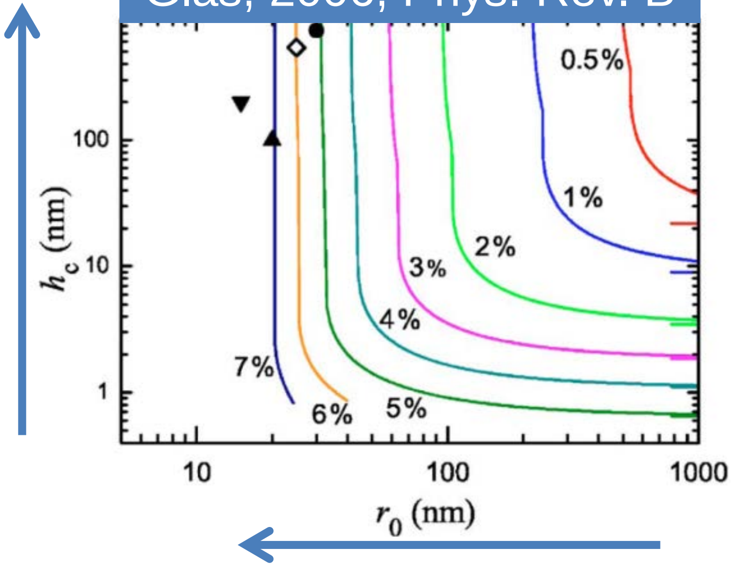




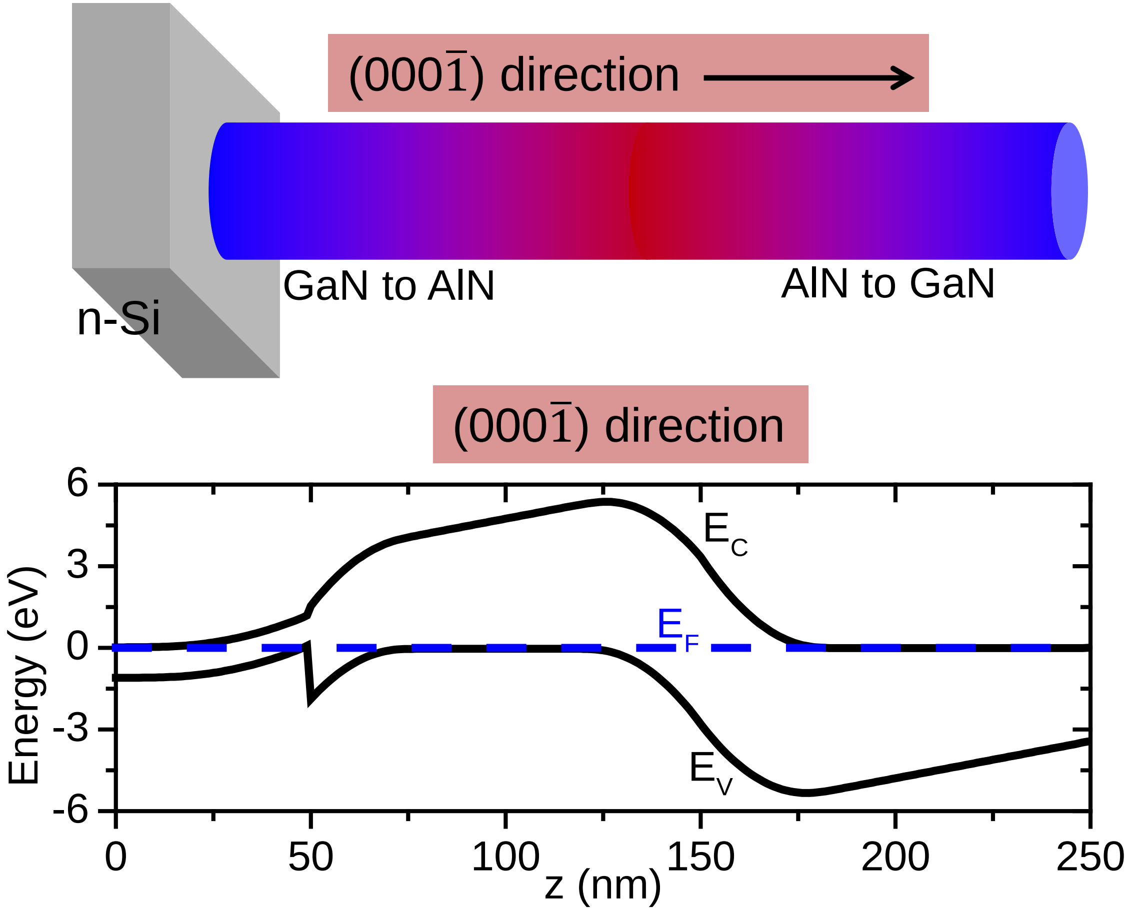
Carnevale et al, APL 2012



Glas, 2006, Phys. Rev. B

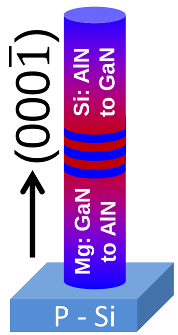


Polarization induced nanowire LED

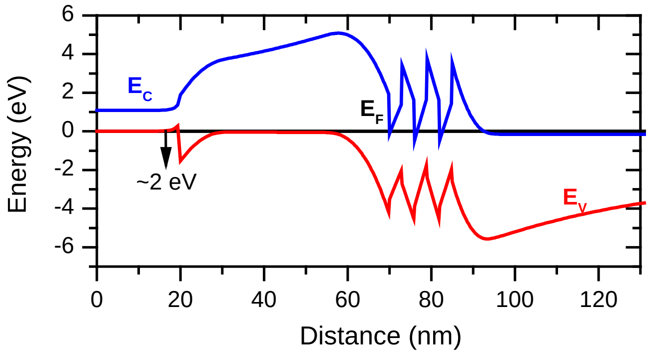


Nanowires grow N-face (Carnevale et al, Nano letters 2013)

N-face polarization induced nanowire LEDs



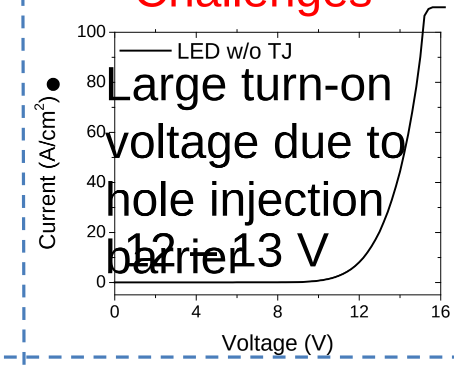
LED on P-Si



Attributes

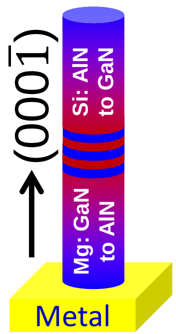
- Right orientation for polarization doping

Challenges

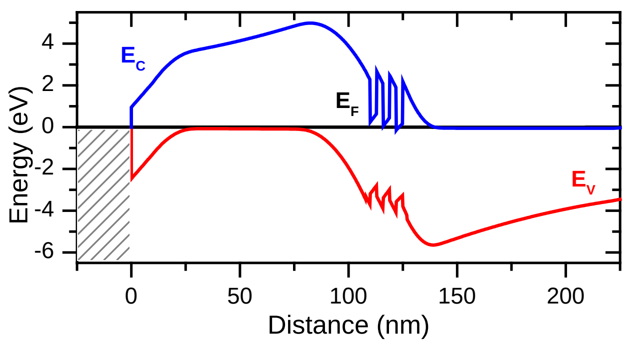


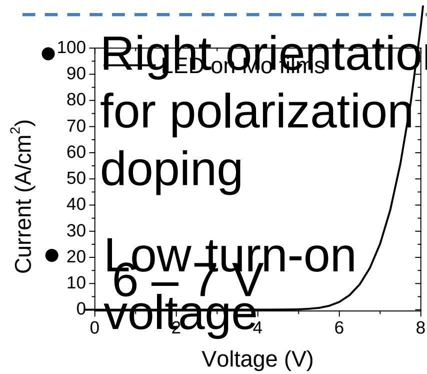
- Large turn-on voltage due to hole injection barrier

12 – 13 V



LED on Metal

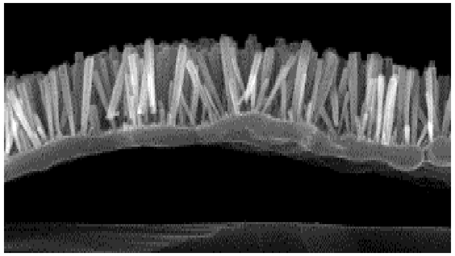


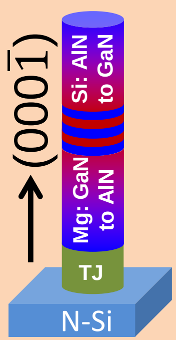


- Right orientation for polarization doping
- Low turn-on voltage

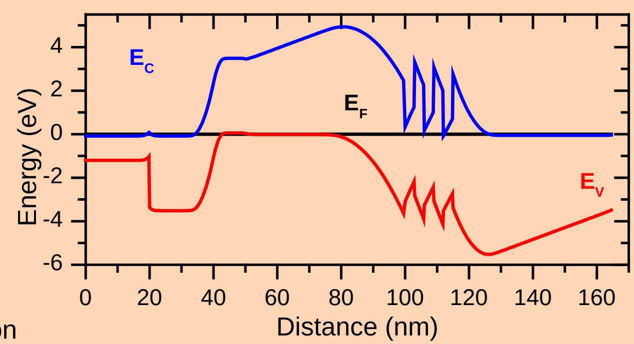
6 – 7 V

- Delamination of metal films





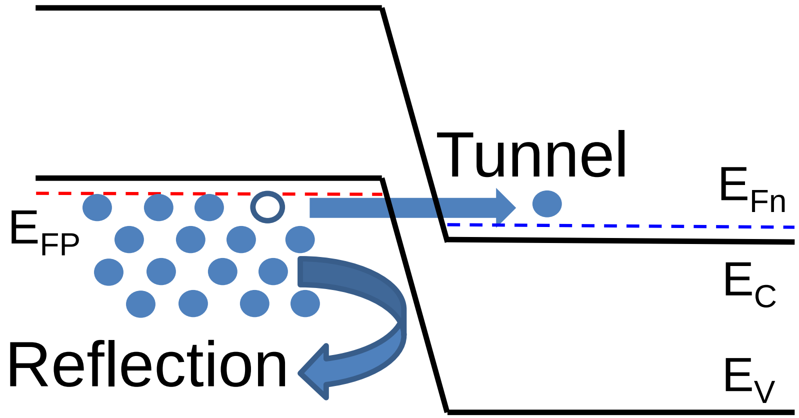
LED w Tunnel Junction



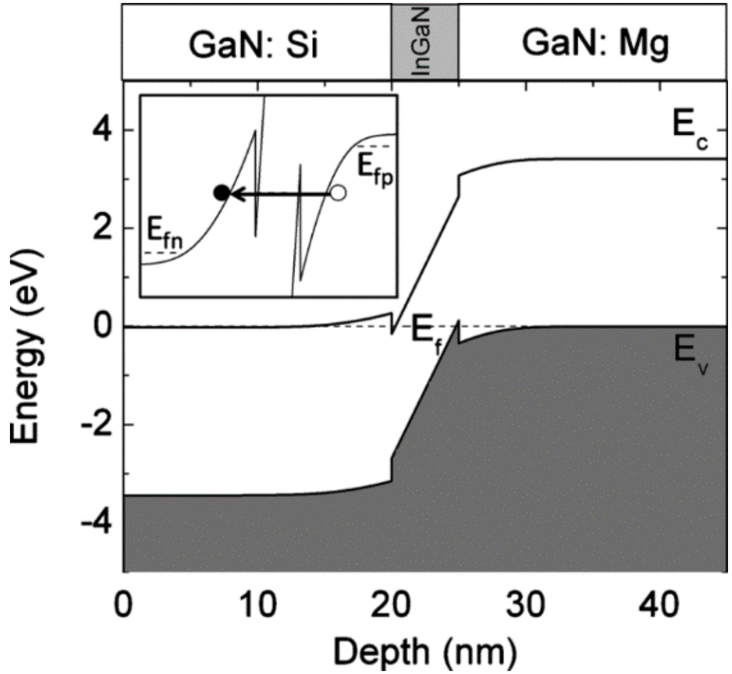
- Right orientation for polarization doping
- Low turn-on voltage
- Si substrate

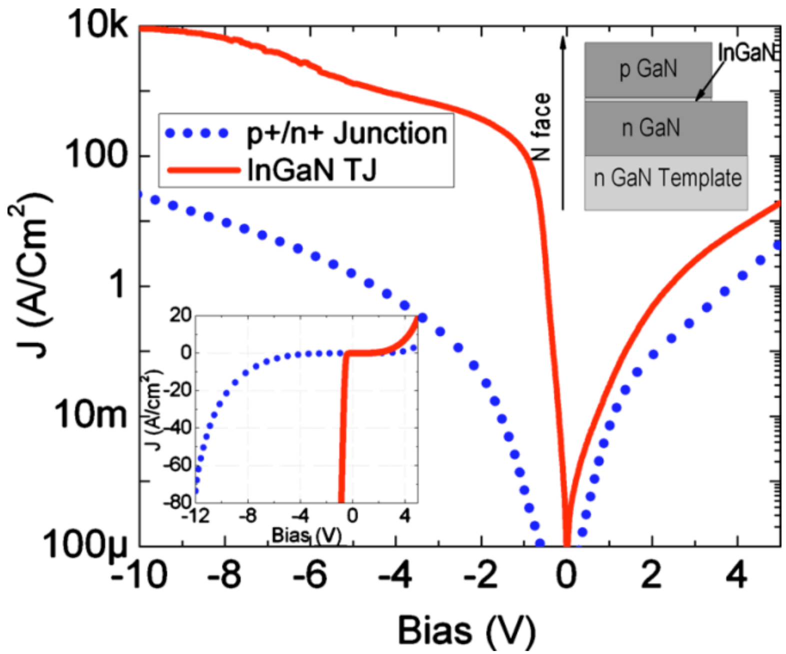
- High Mg doping
- Use of different temperature for different part of the structure

Polarization Engineered III-N Tunnel Junction



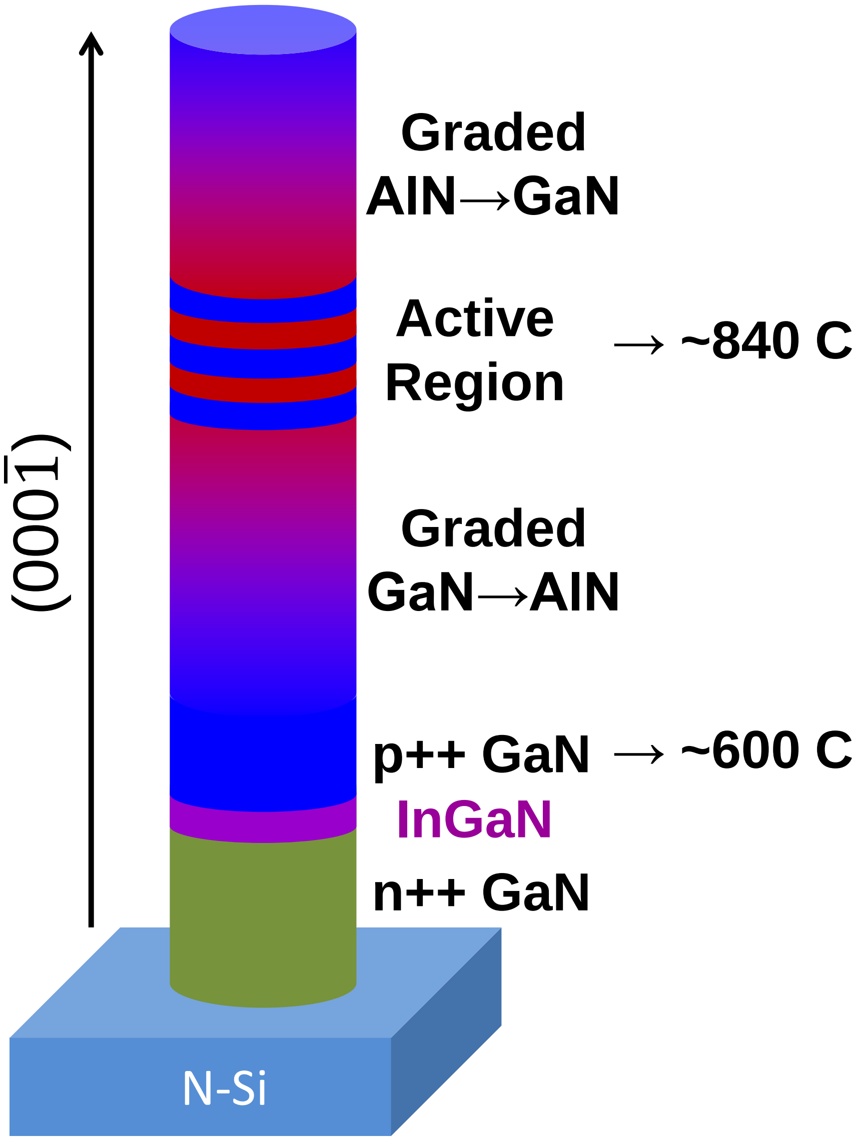
Tunnel junction
- High doping
- Narrow depletion width
- Electron tunneling

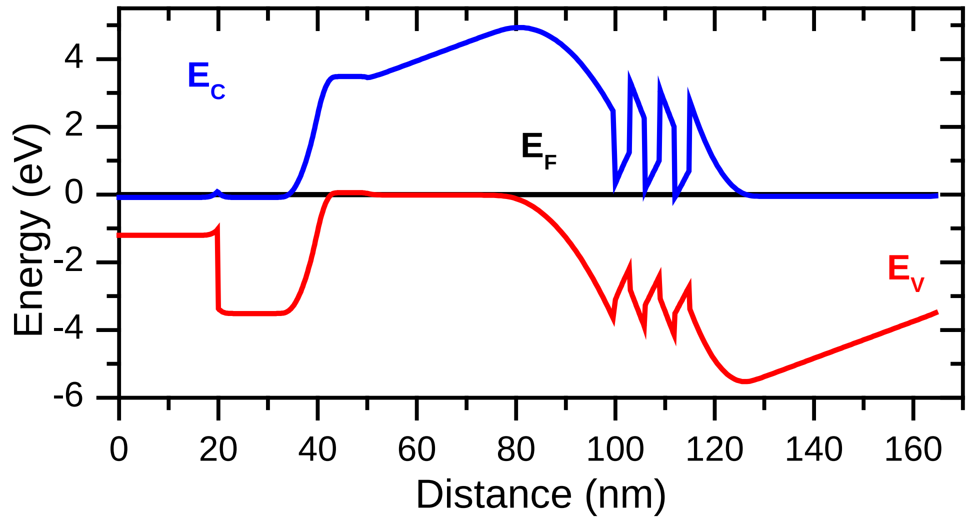




S Krishnamoorthy et al, APL 2010

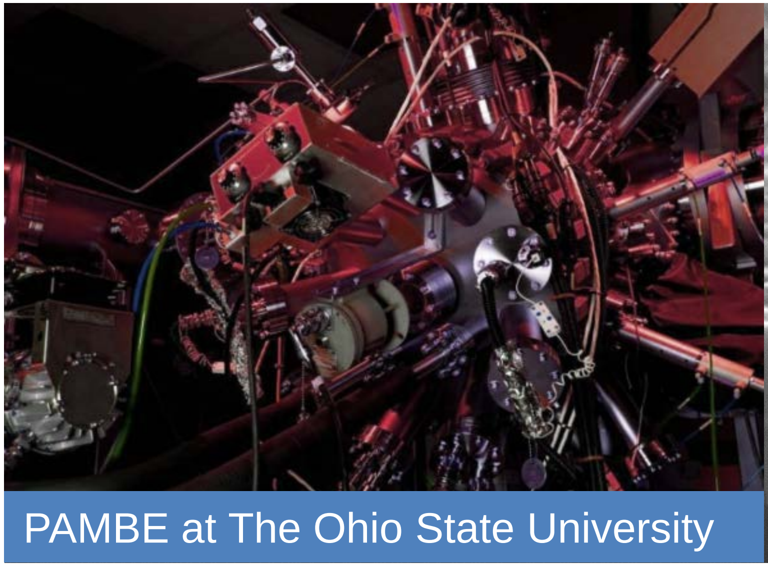
Nanowire tunnel junction UVLED design

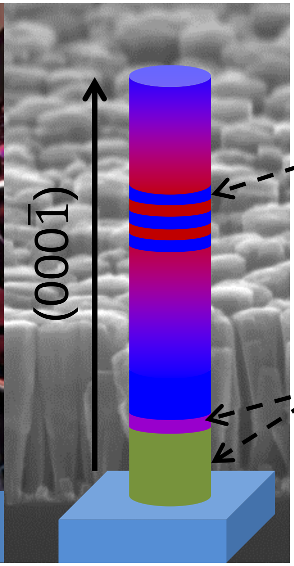


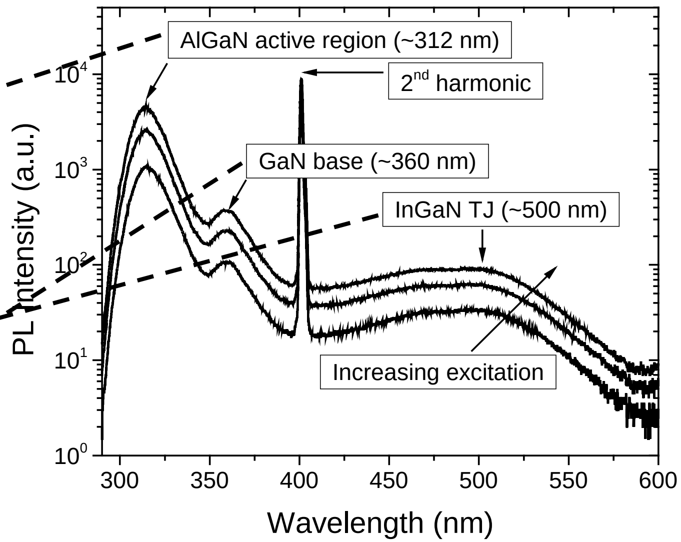


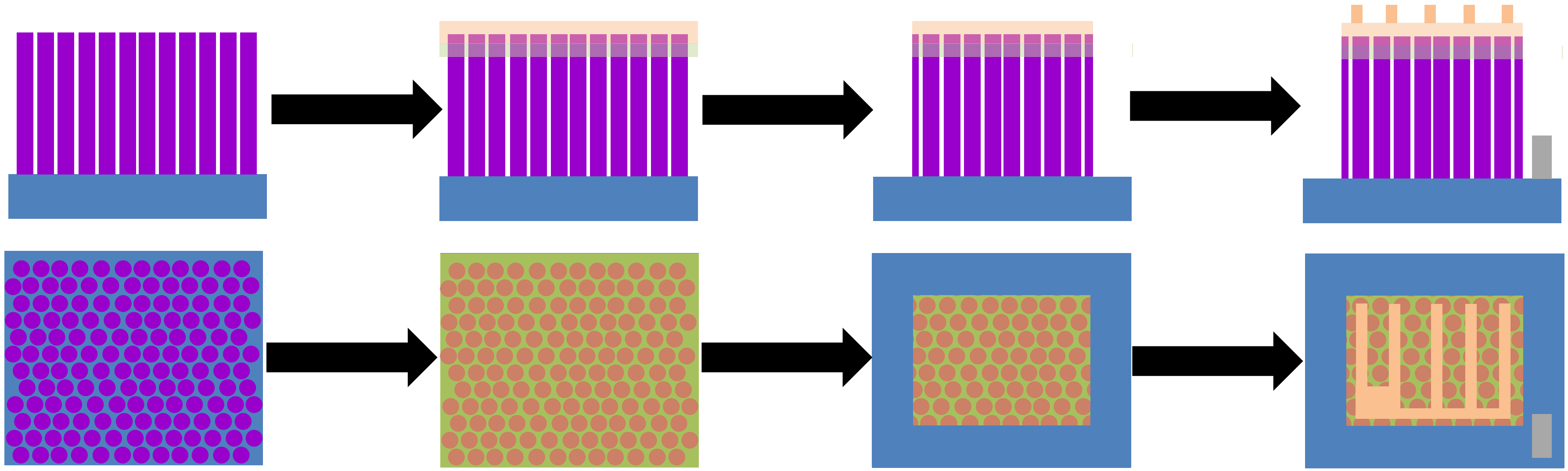
- Grown at low temperature.
- AlGaN active region needs to be grown at high temperature.

Nanowire LED fabrication

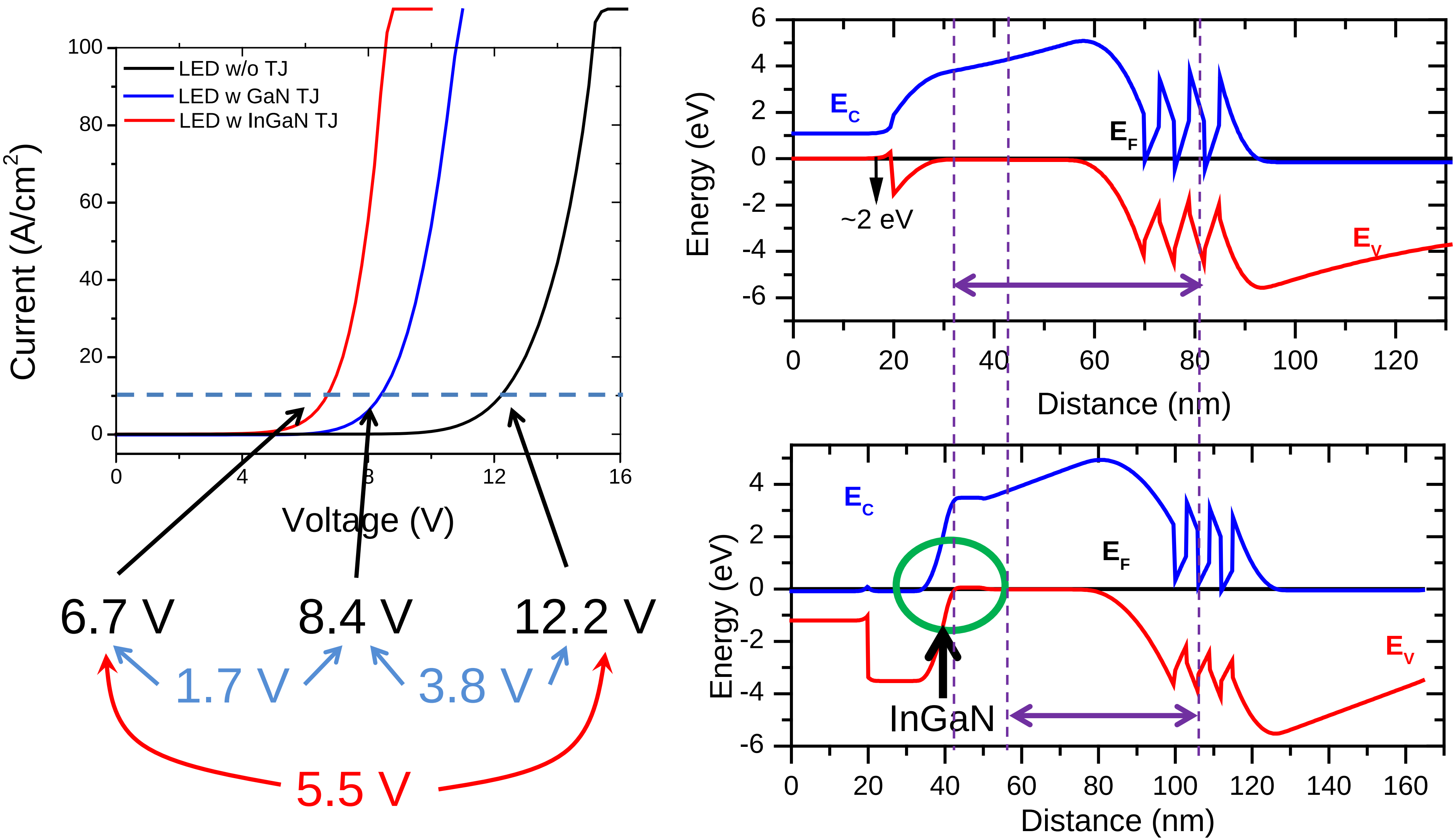




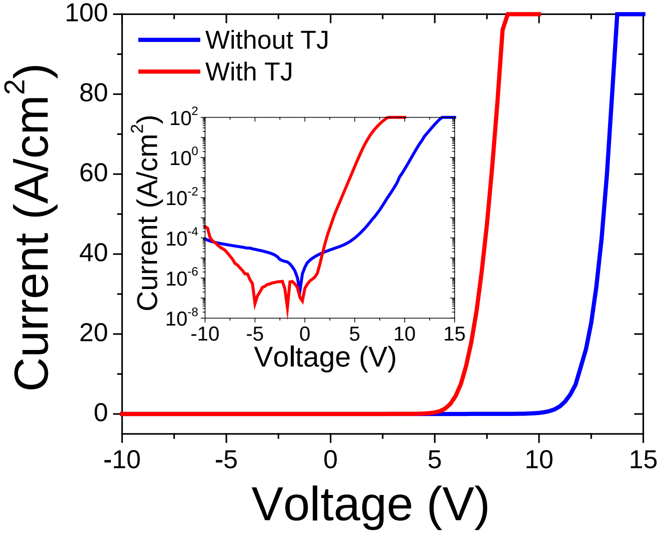


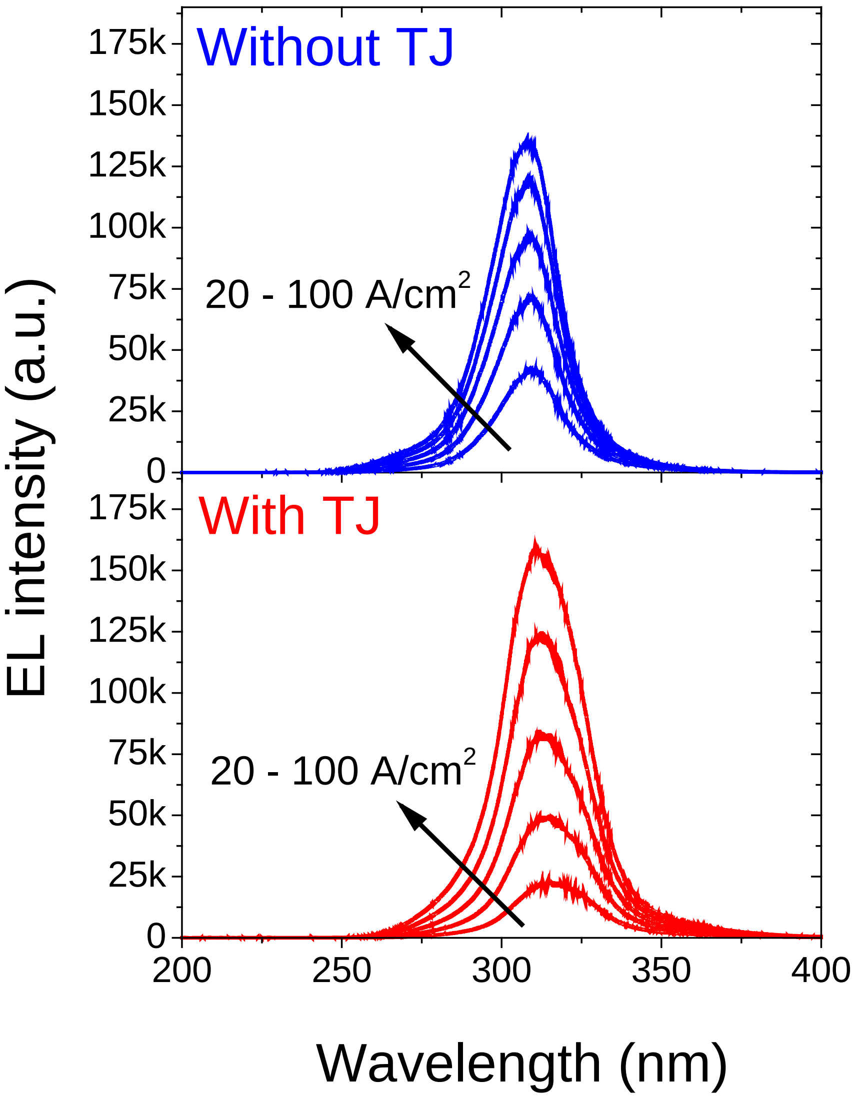


Low $V_{turn\text{-}on}$ on in TJ integrated nanowire LEDs



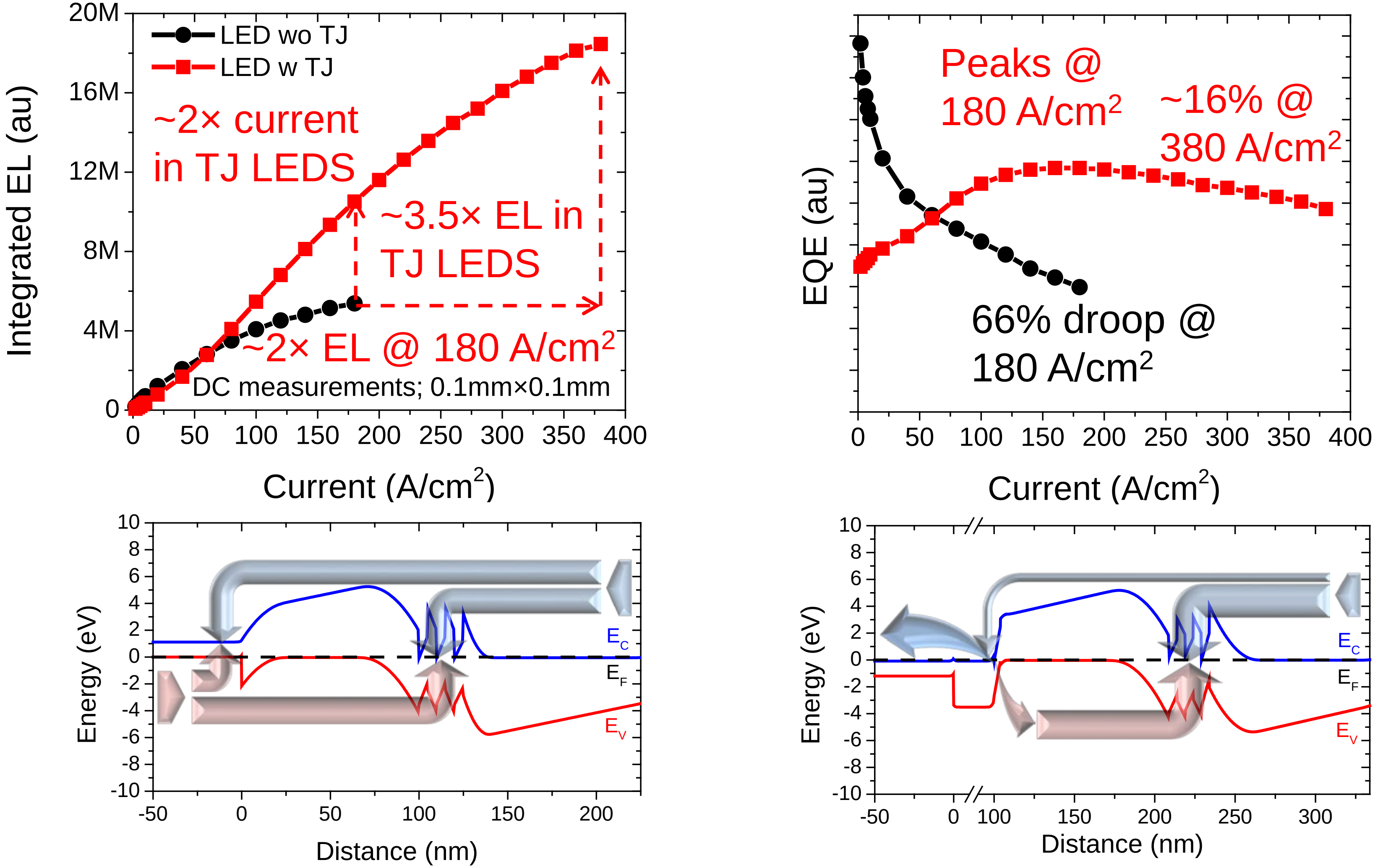
UV emission from TJ integrated nanowire LED





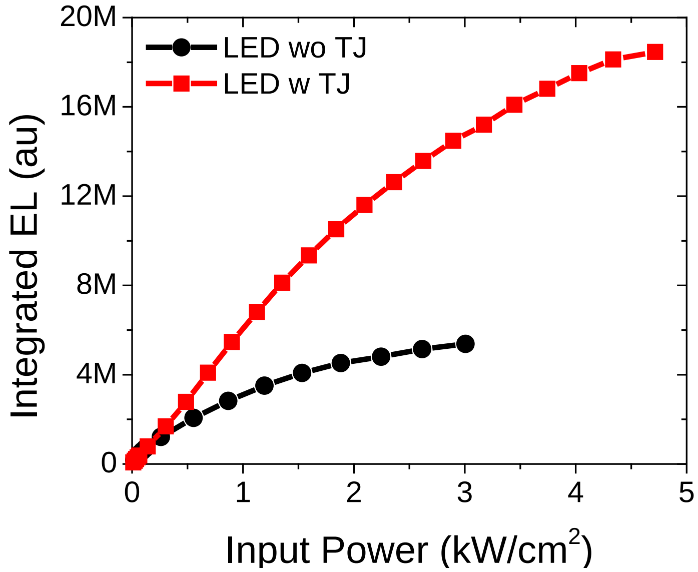
- Better forward and reverse bias characteristics in LEDs with TJ
- ~310 nm UV emission from both LEDs without TJ and with TJ.
- Enhanced EL in LEDs with TJ

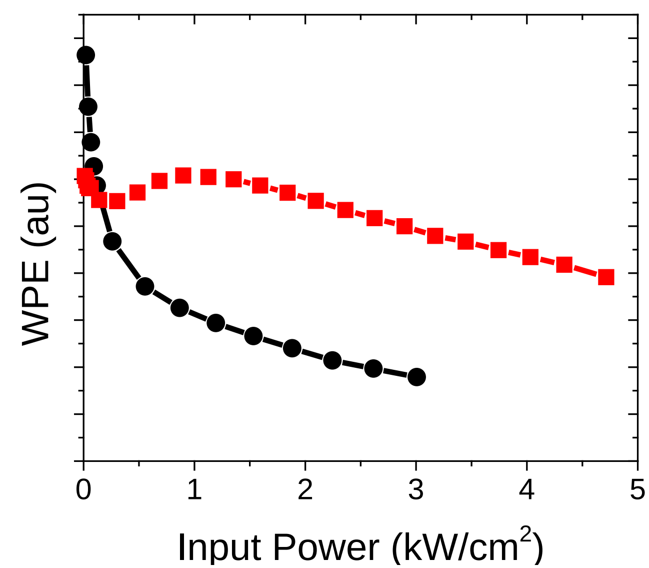
Suppressed efficiency droop in TJ integrated LEDs

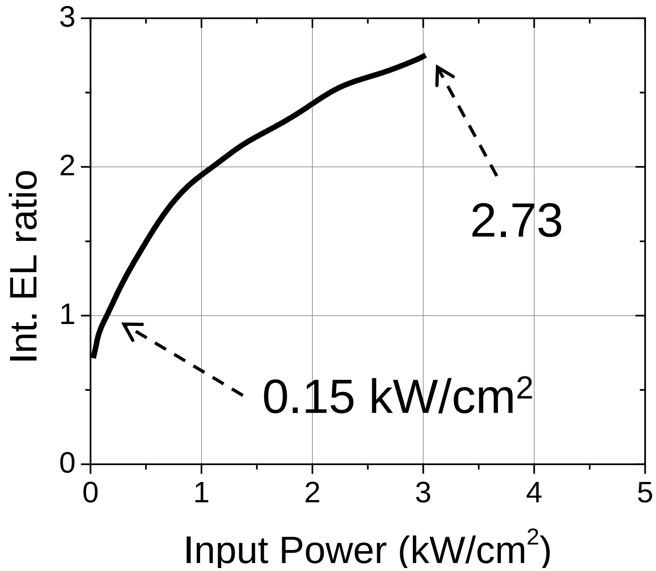


- Auger recombination
- Electron leakage
- Junction heating

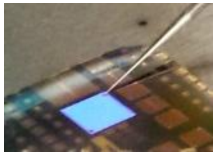
Increased wall plug efficiency





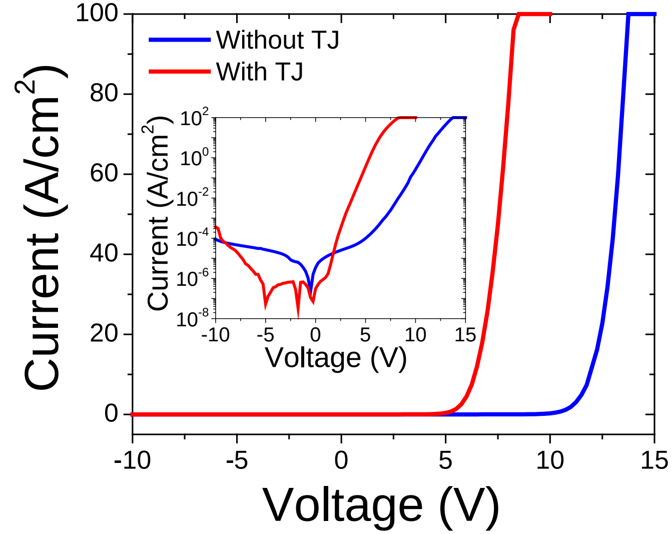


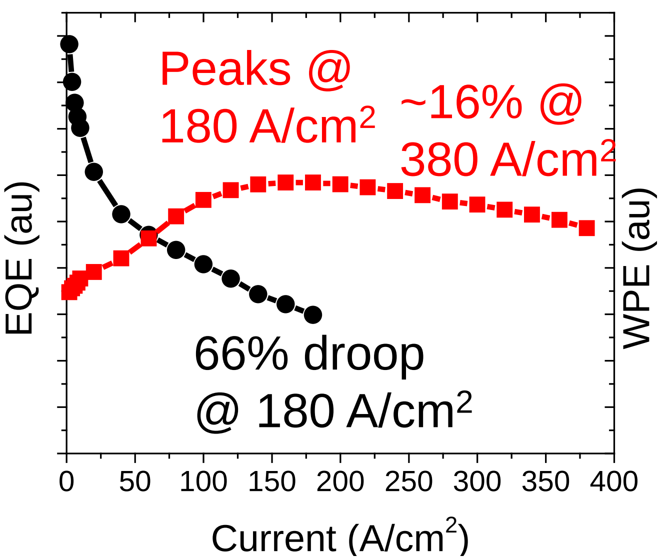
- Effect of both increased hole injection and decreased operating voltage
- Max. wall plug efficiency @1 kW/cm^2
- ~2× light output at this point

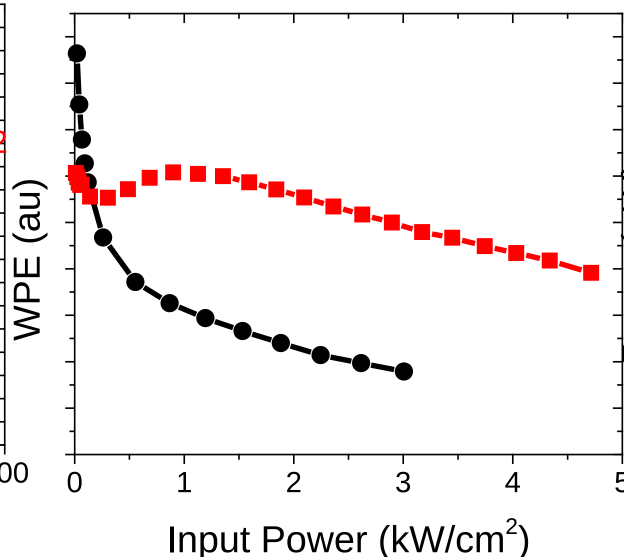


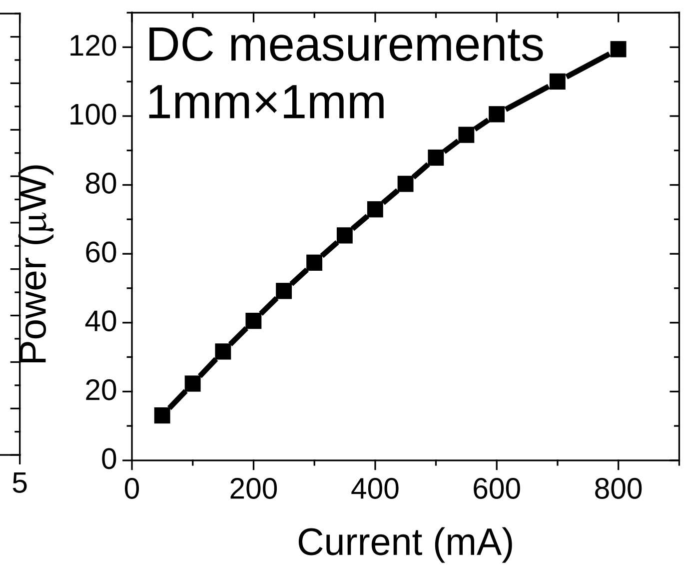
Summary

- Hole injection using tunnel junction in nanowire UV LEDs
- Decreased turn on voltage
- Suppressed efficiency droop
- Increased wall plug efficiency









Polarization Hole Engineering in Deep-Ultraviolet Nanowire LEDs

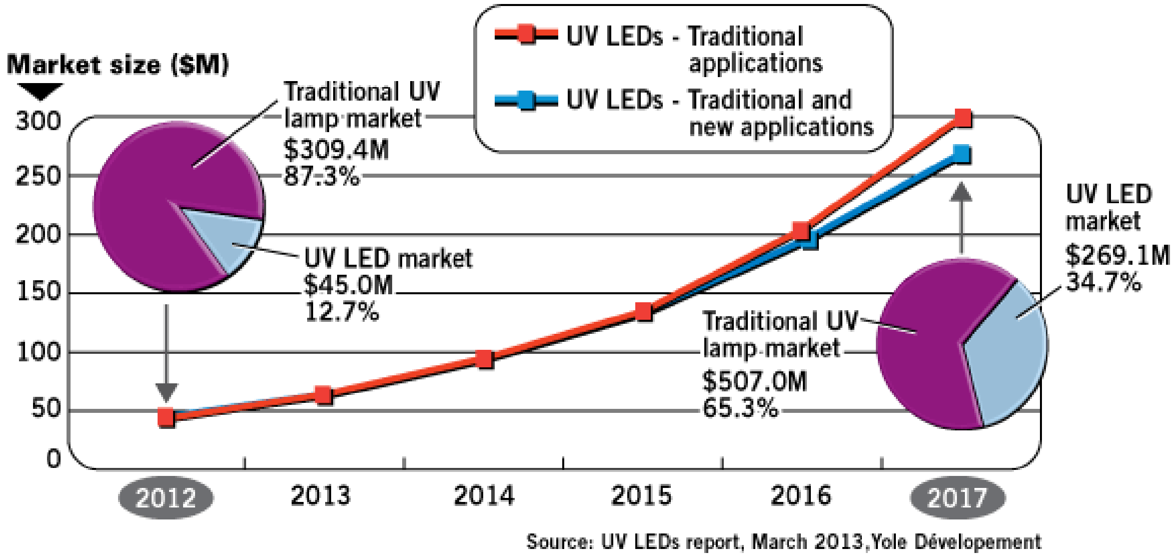
ATM Golam Sarwar[1], Santino D Carnevale[1], Thomas F Kent[2], Brelon J May[2], Fan Yang[2], Gerd Duscher[3], David D McComb[2], and Roberto C Myers[1,2]

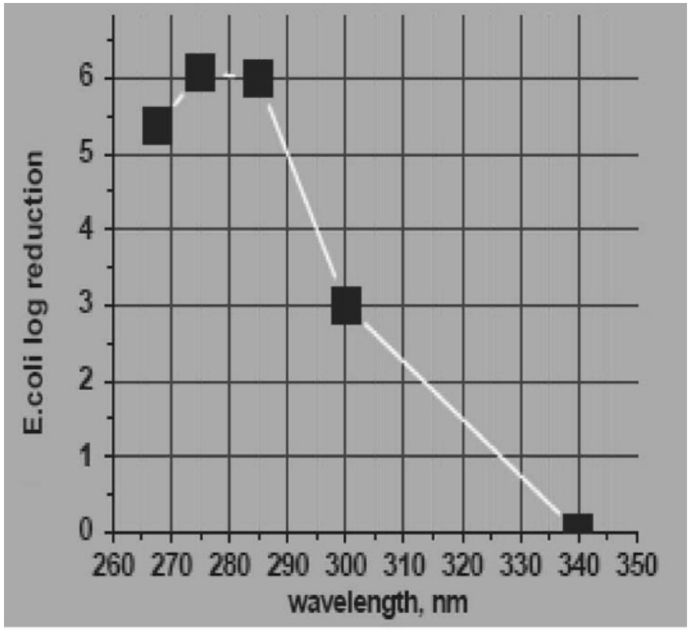
[1]Department of Electrical and Computer Engineering, The Ohio State University
[2]Department of Materials Science and Engineering, The Ohio State University
[3]Department of Materials Science and Engineering, University of Tennessee

Outline:

1. DUV emitter application
2. Solid state DUV emitter: challenges
3. Nanowire and polarization doping
4. Nanowire UVLEDs

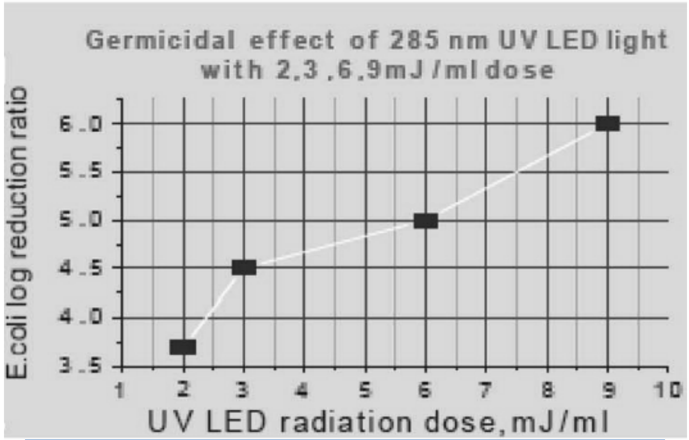
Deep ultraviolet (DUV) emitter: Applications





(a)

- UV solid state emitters is a rapidly growing market
  - UV curing of adhesives
  - Water disinfection
  - Chemical Agent detection



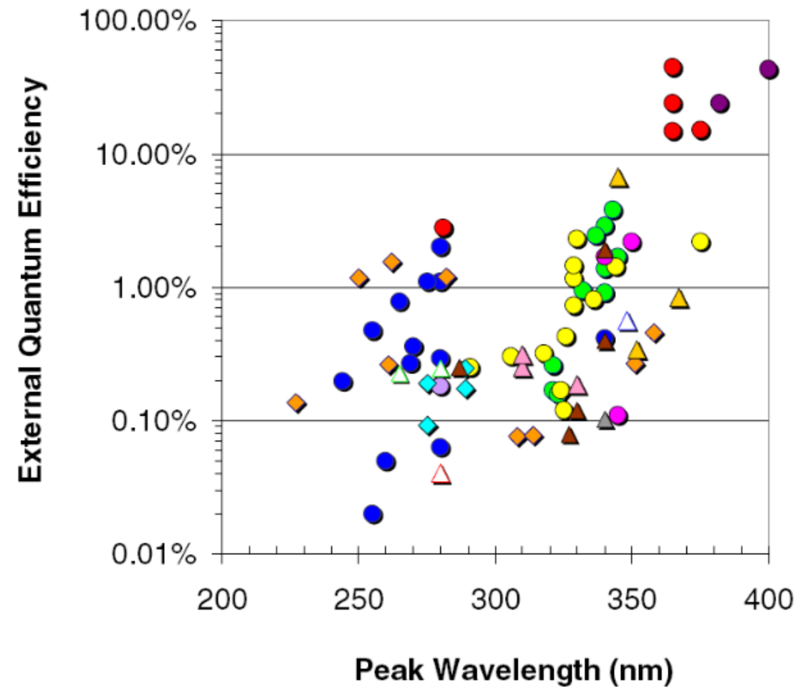
Shur et al, IEEE Trans. Elec. Dev., 2010

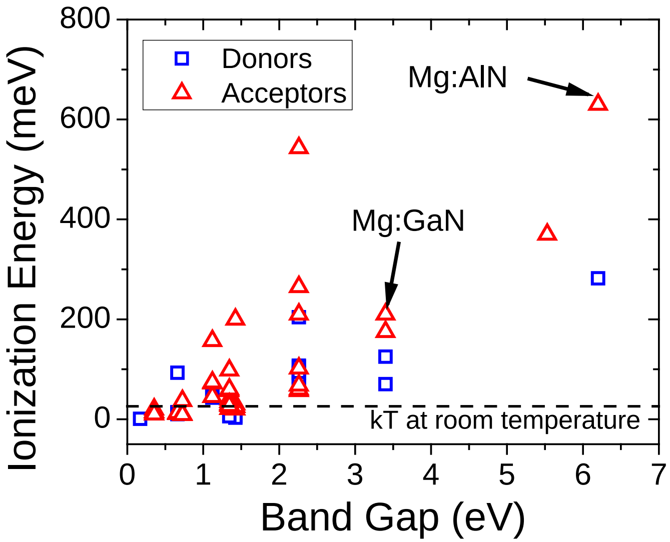
- Replacement of bulky, toxic Hg arc lamps

- Applications require high output power, EQE

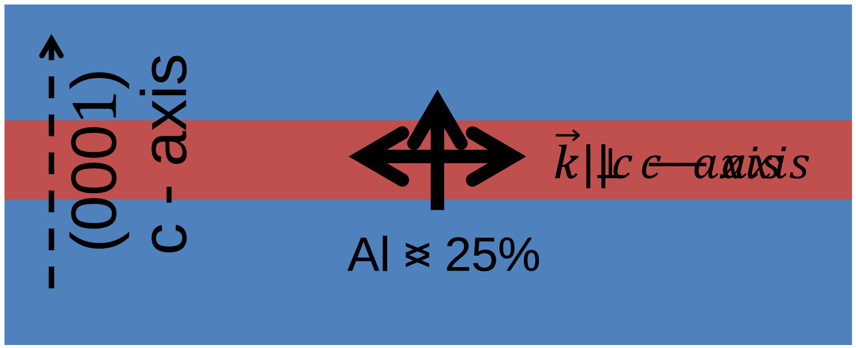
Solid state DUV LEDs: challenges

- Currently Al-rich AlGaN is used
- Poor efficiency due to
  - High TDD in substrates
  - Poor dopant activation
  - Optically active defects
  - TE to TM switch

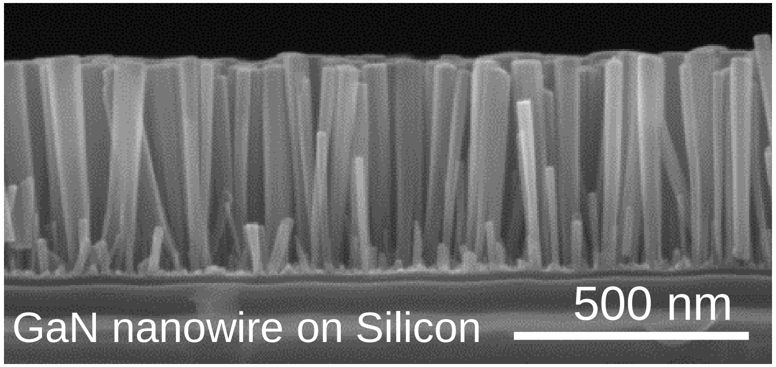


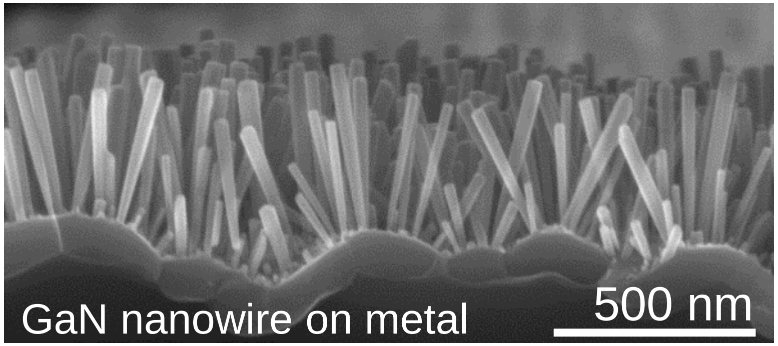


Values from: http://www.ioffe.ru/SVA/NSM/, Taniyasu et al., 2006, Nature

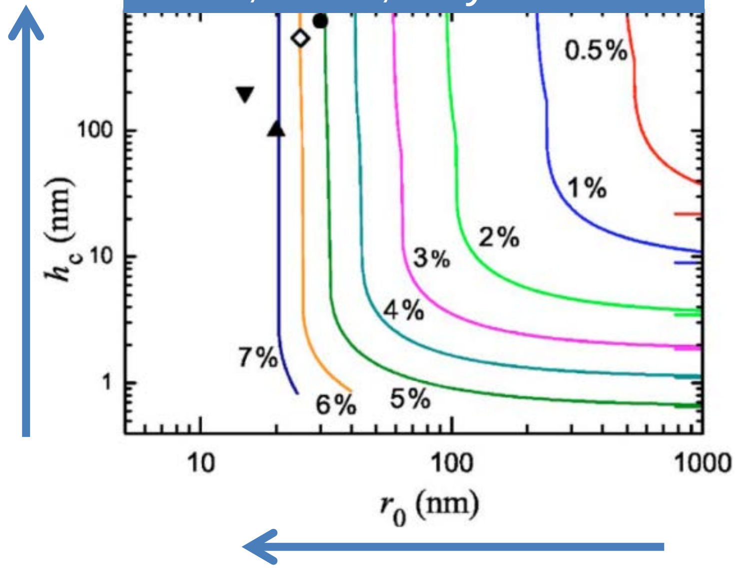


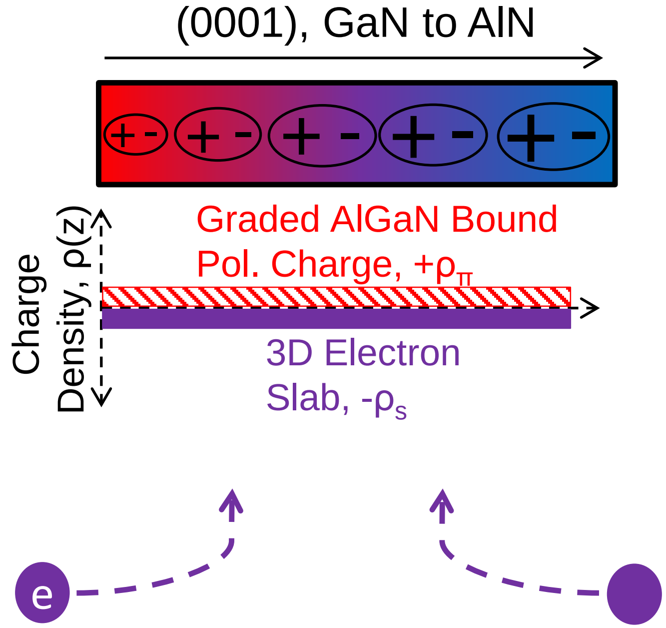
Nanowires and polarization doping





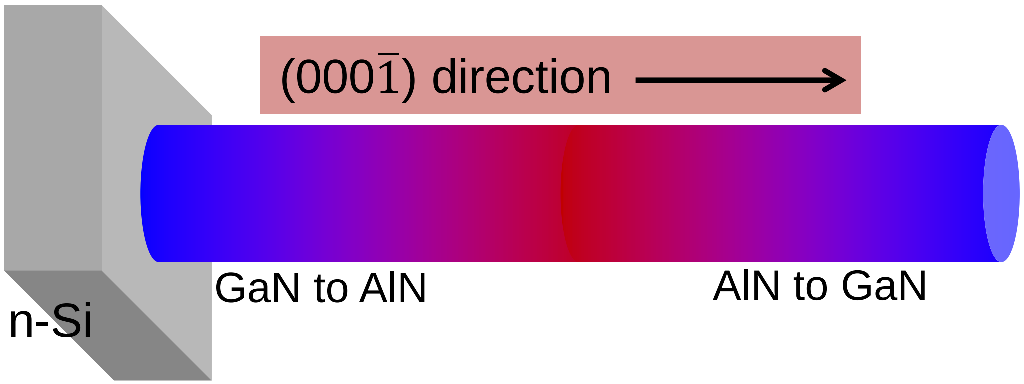
Glas, 2006, Phys. Rev. B

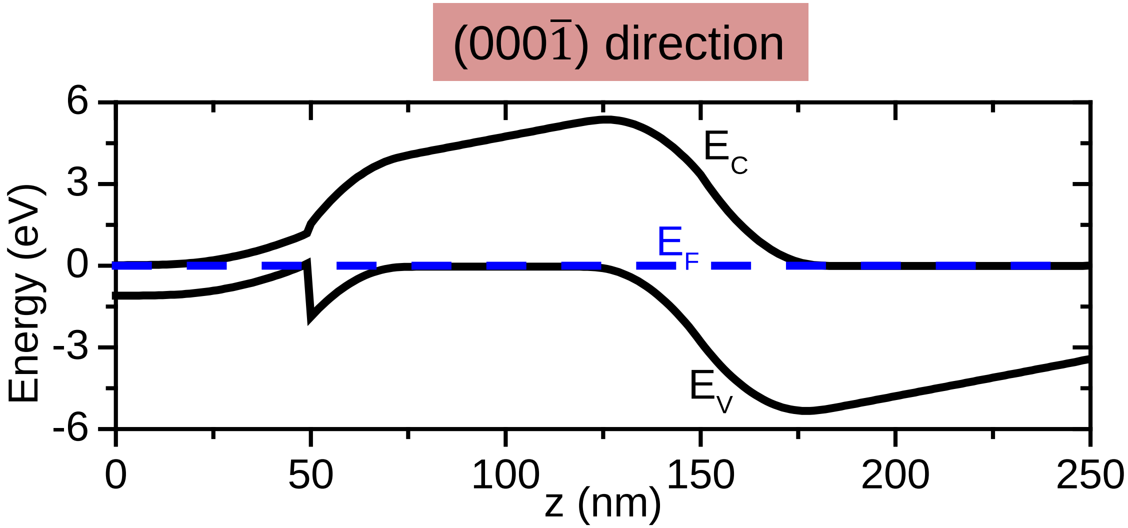




Jena et al., APL 2002

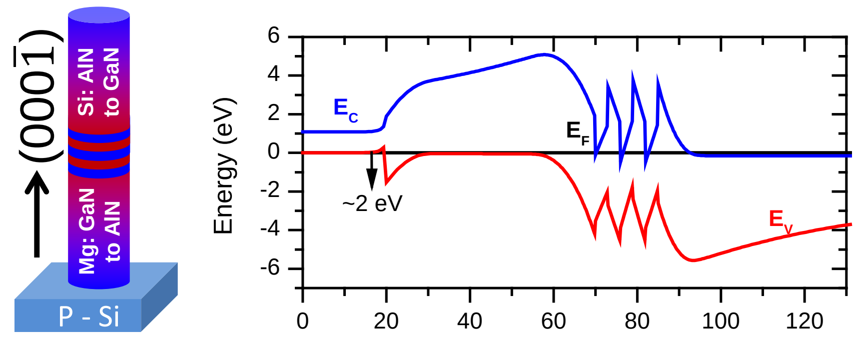
Polarization induced nanowire (PIN) LEDs



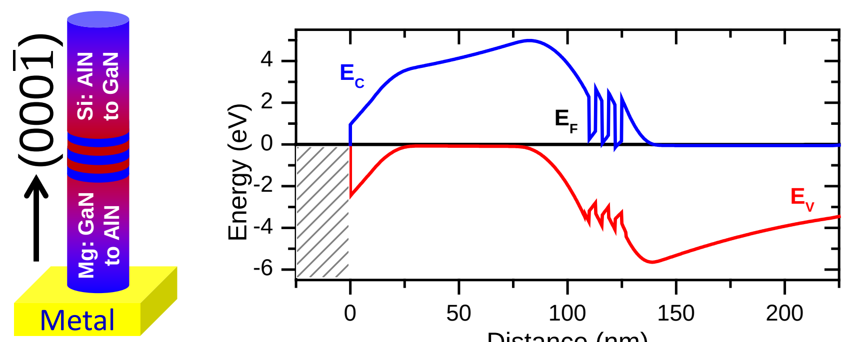


Nanowires grow N-face (Carnevale et al, Nano letters 2013)

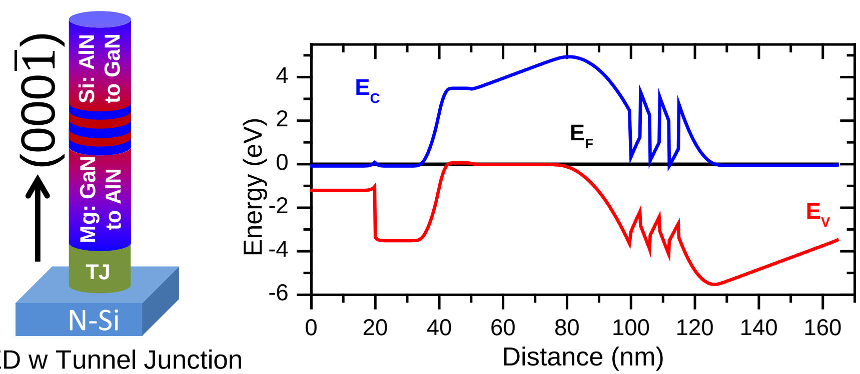
N-face polarization induced nanowire(PIN) LEDs



LED on P-Si

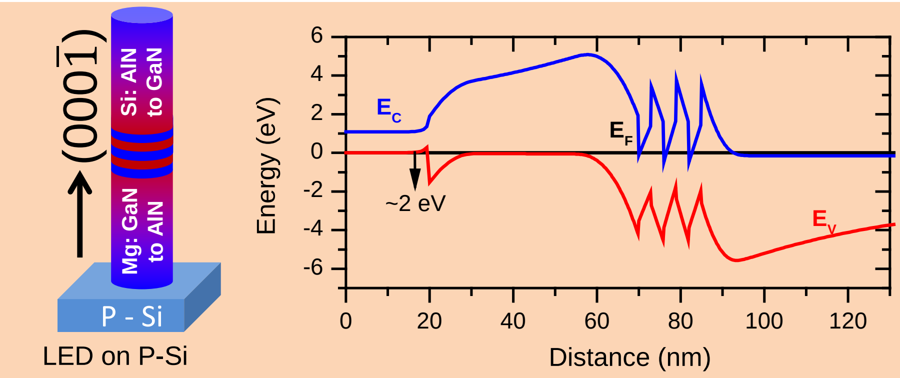


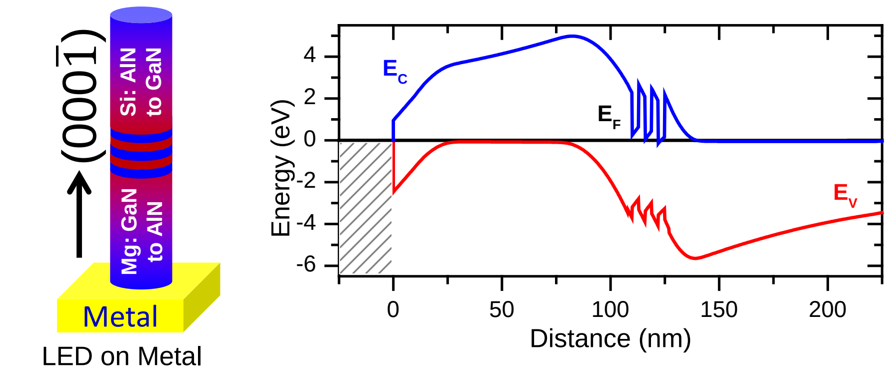
LED on Metal

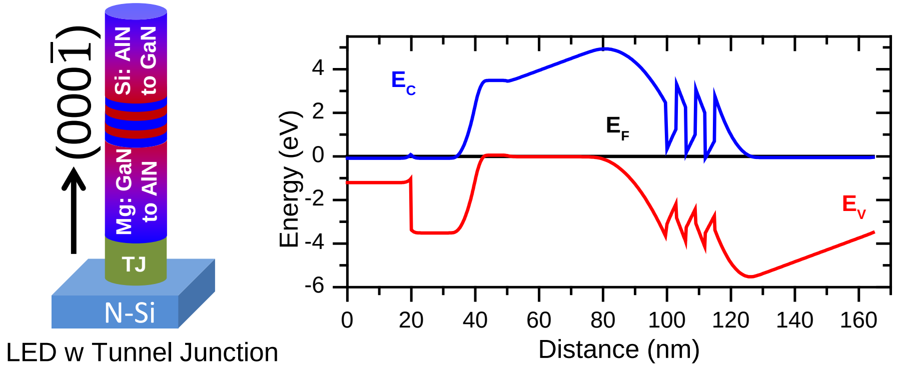


LED w Tunnel Junction

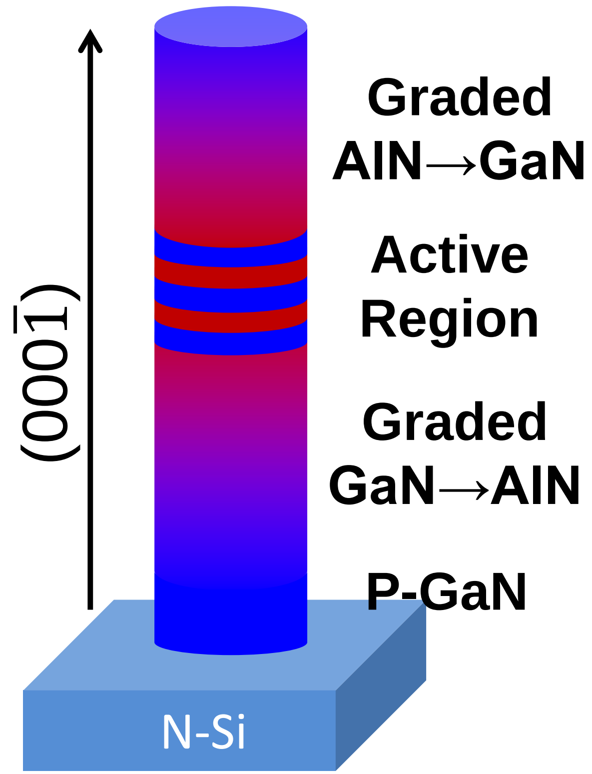
PINLEDs on p-Si

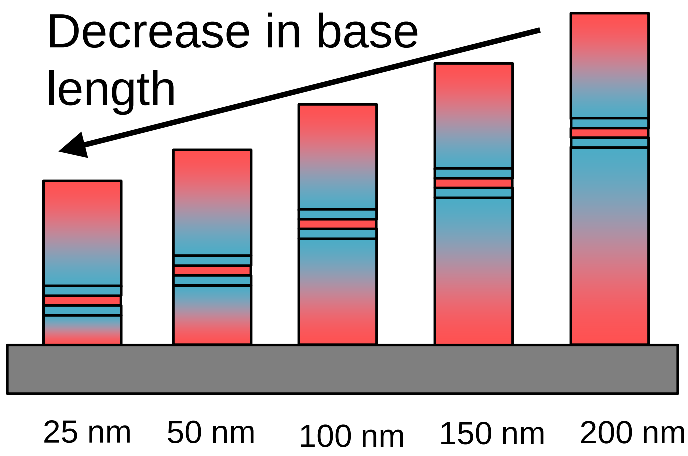


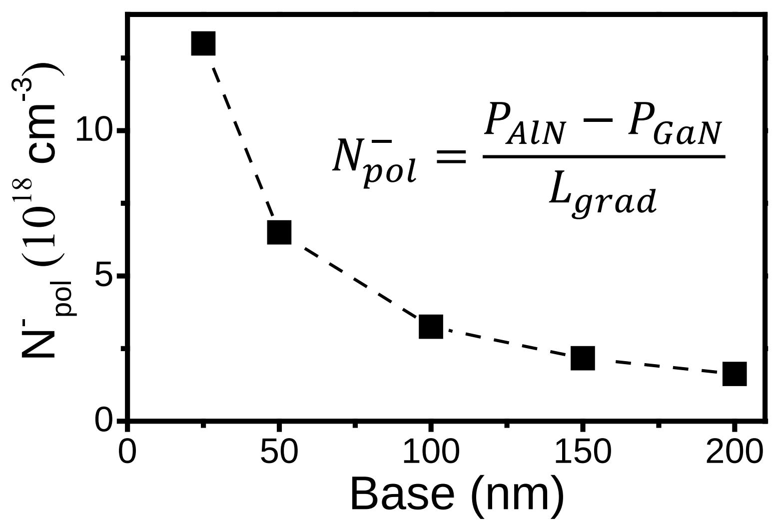




Systematic study of polarization hole doping

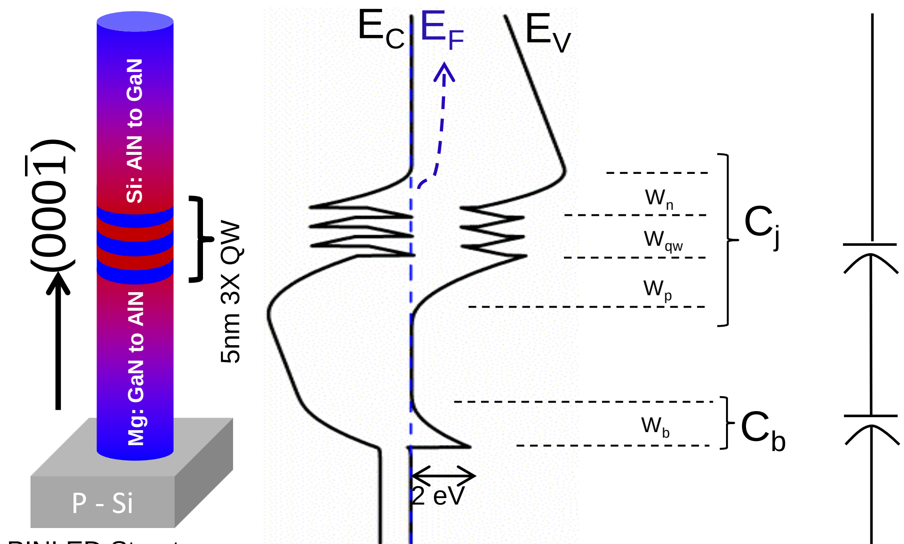




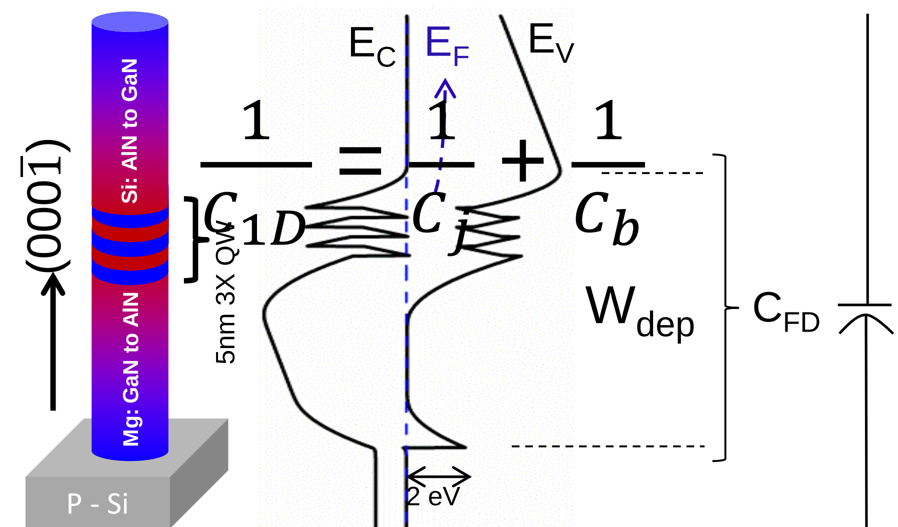


- Polarization induced hole doping is debatable.
- Aggressive p-grading

Effect of composition gradient on capacitance

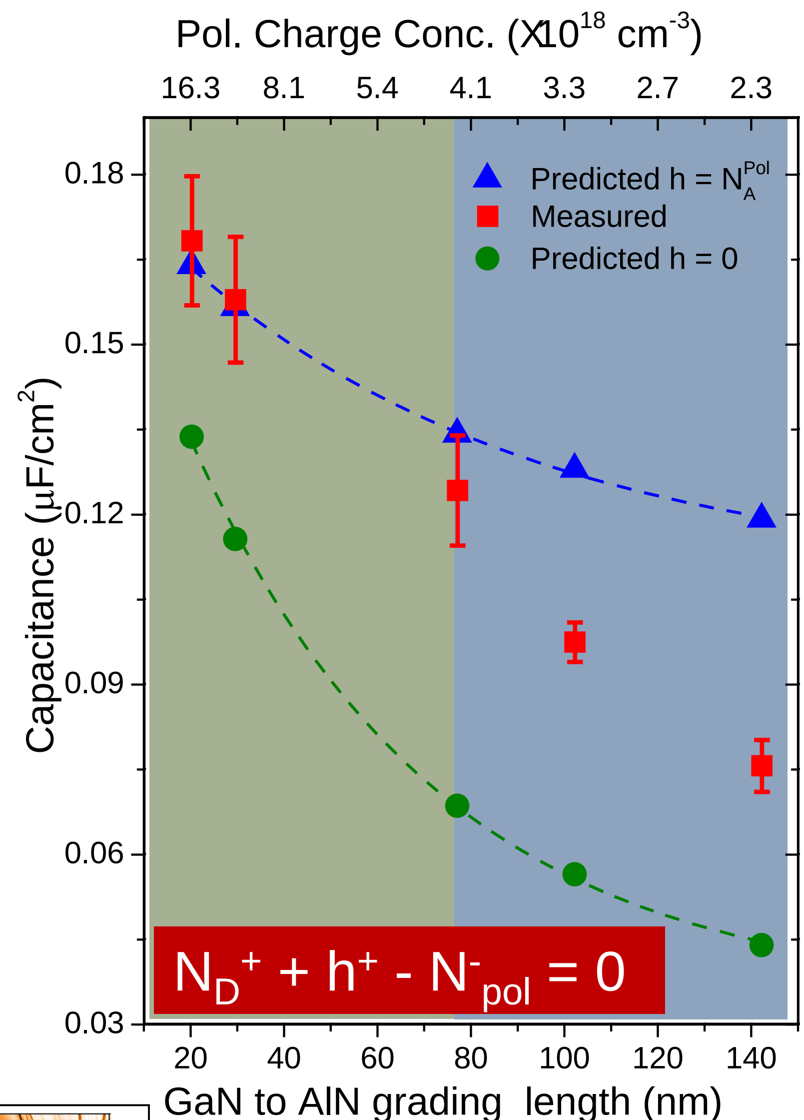


PINLED Structure



$$\frac{1}{C_{1D}} = \frac{1}{C_j} + \frac{1}{C_b}$$

PINLED Structure

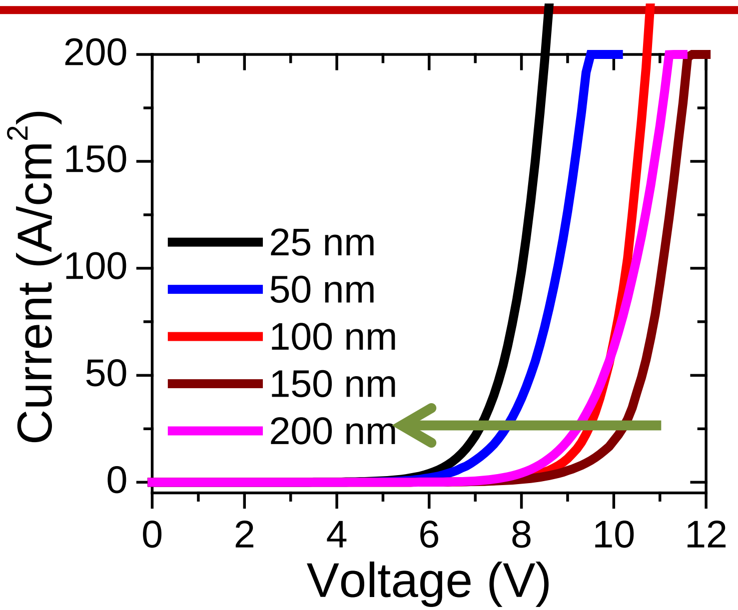


AIP Applied Physics Letters

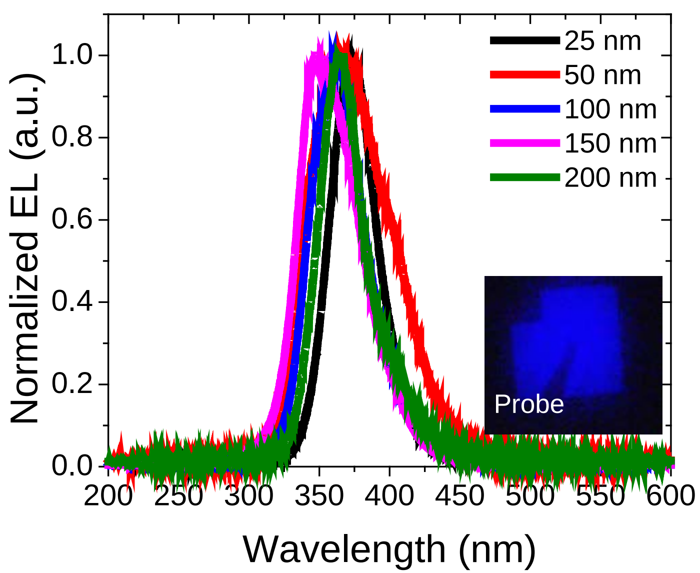
Tuning the polarization-induced free hole density in nanowires graded from GaN to AlN

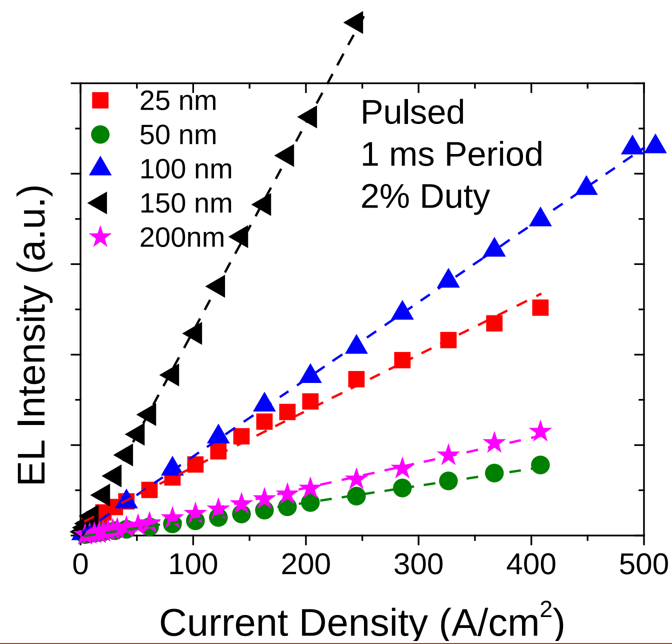
A. T. M. Golam Sarwar, Santino D. Carnevale, Thomas F. Kent, Fan Yang, David W. McComb, and Roberto C. Myers

Effect of composition gradient on IV

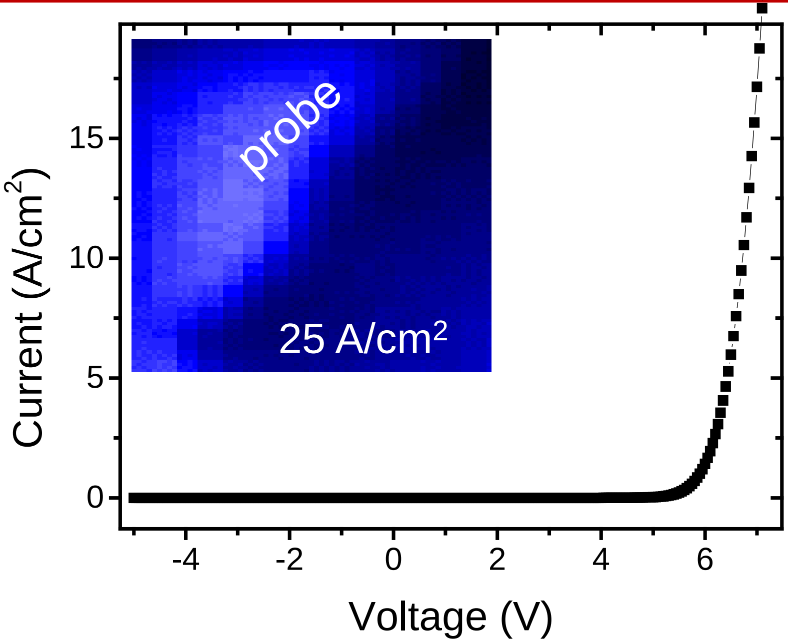


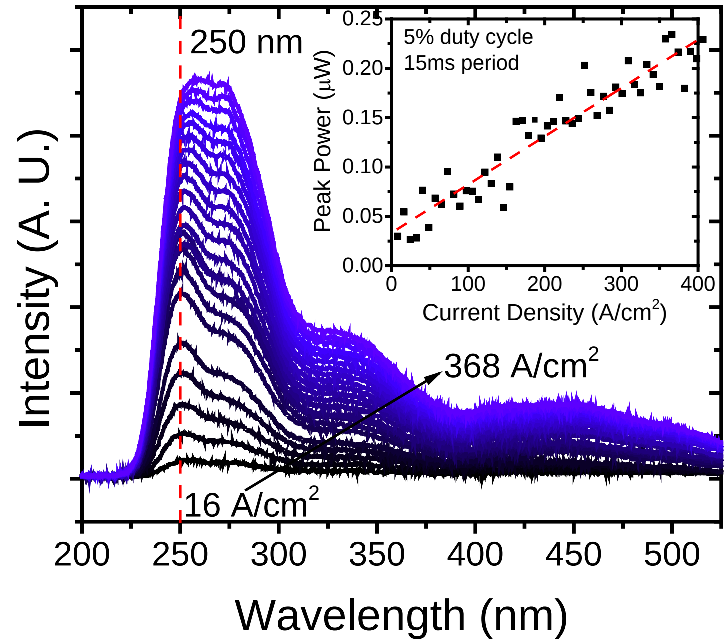
- Decreased turn on voltage
- UV emission from active region
- Decreased EL with aggressive grading





DUV emission from AlGaN active region





IOP Publishing Nanotechnology

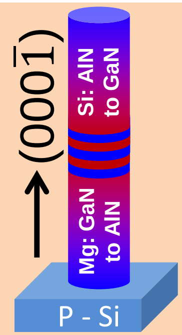
Nanotechnology **25** (2014) 455201 (6pp) doi:10.1088/0957-4484/25/45/455201

Deep ultraviolet emitting polarization induced nanowire light emitting diodes with $Al_xGa_{1-x}N$ active regions

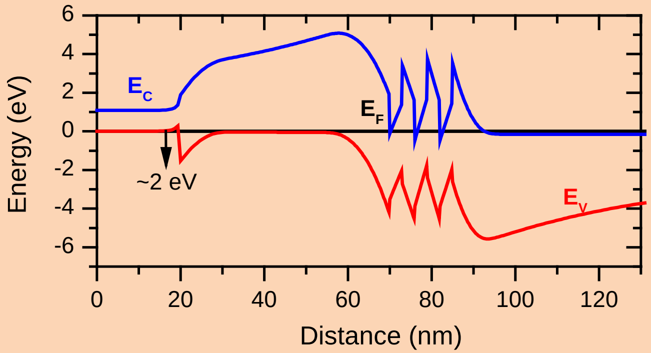
Thomas F Kent[1], Santino D Carnevale[2], A T M Sarwar[2], Patrick J Phillips[3], Robert F Klie[3] and Roberto C Myers[1,2]

[1] Department of Materials Science and Engineering, The Ohio State University, Columbus, OH, USA
[2] Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH, USA
[3] Department of Physics, University of Illinois at Chicago, Chicago, IL 60607, USA

PINLEDs on p-Si



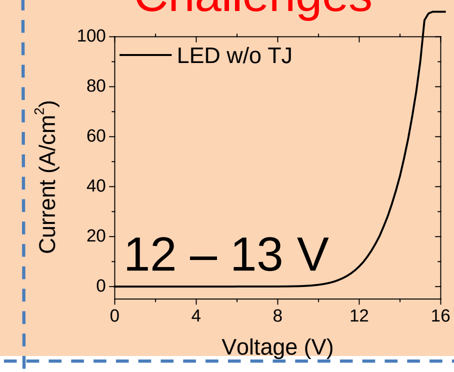
LED on P-Si

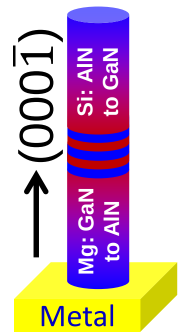


Attributes

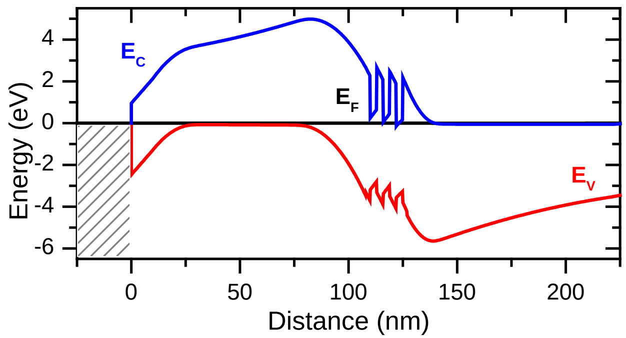
- Right orientation for polarization doping
- DUV emission

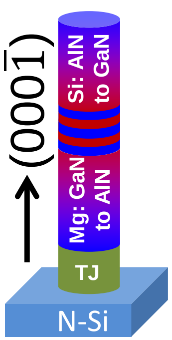
Challenges



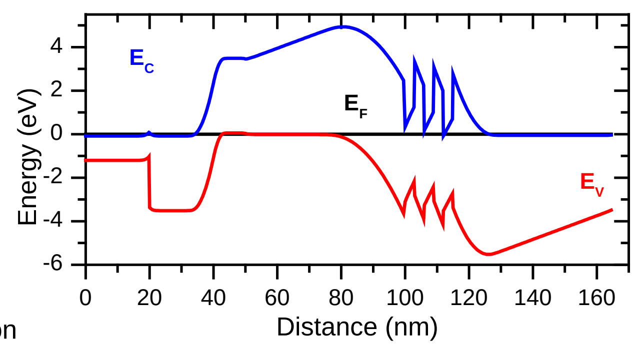


LED on Metal

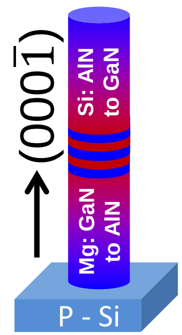




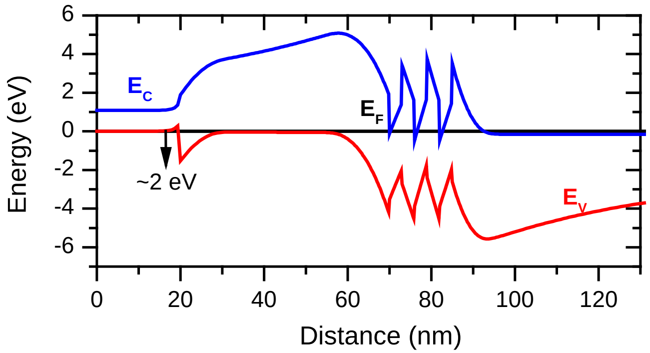
LED w Tunnel Junction



PINLEDs on p-Si



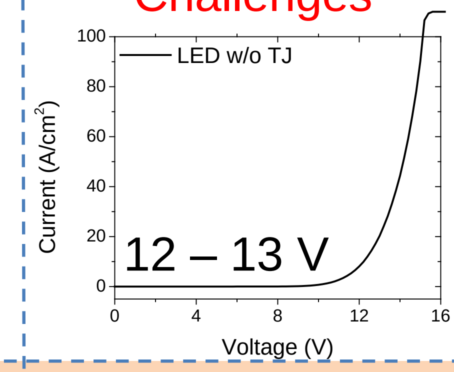
LED on P-Si

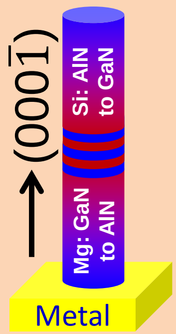


Attributes

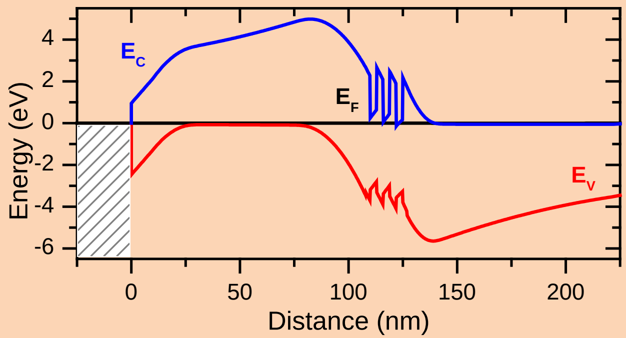
- Right orientation for polarization doping
- DUV emission

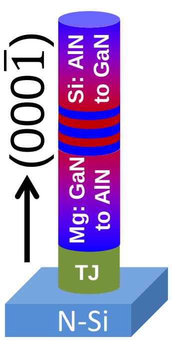
Challenges



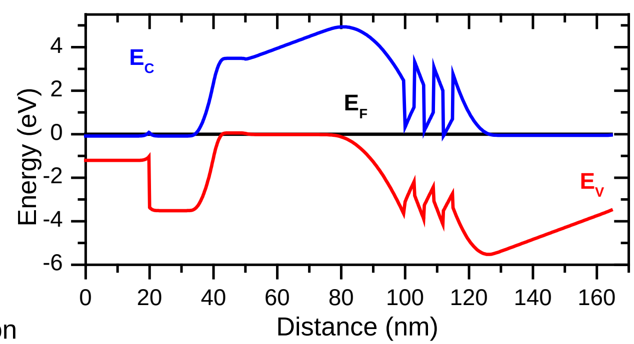


LED on Metal

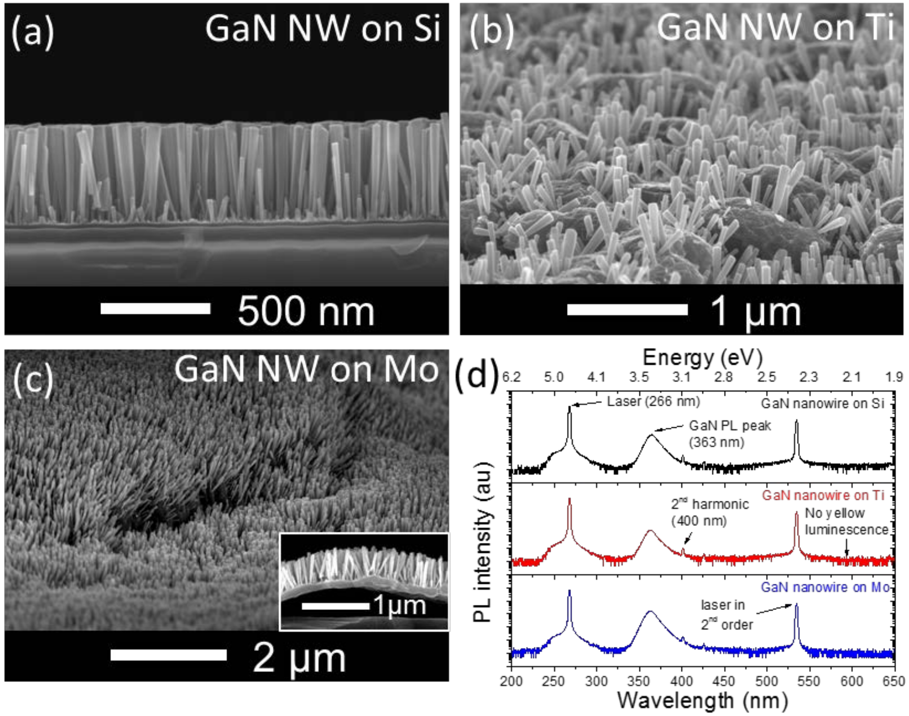


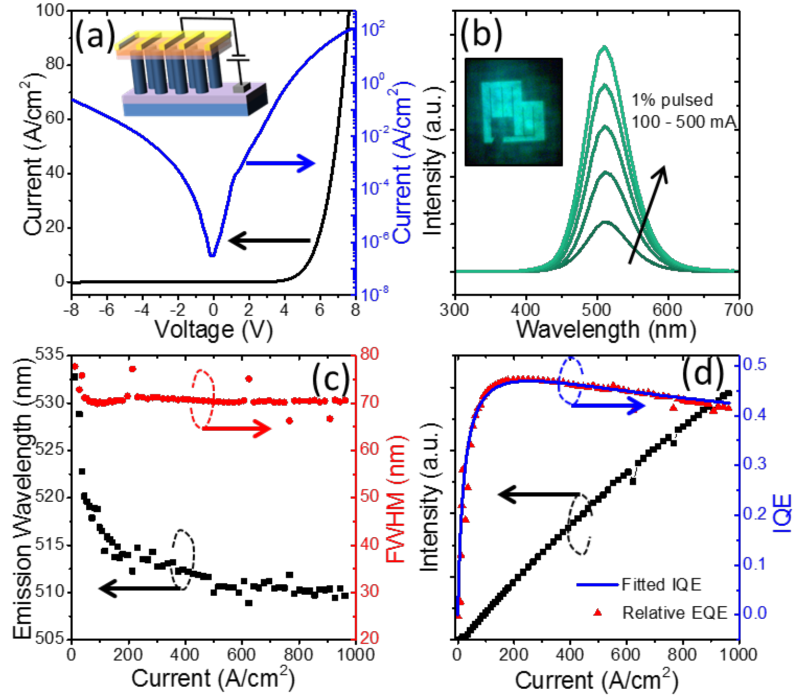


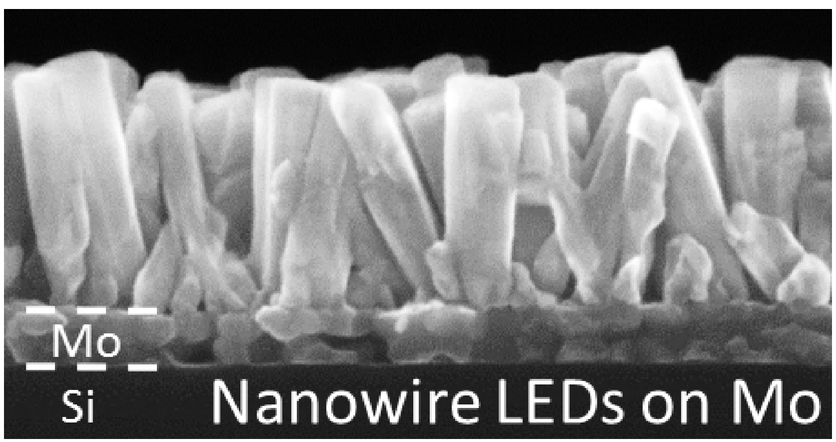
LED w Tunnel Junction

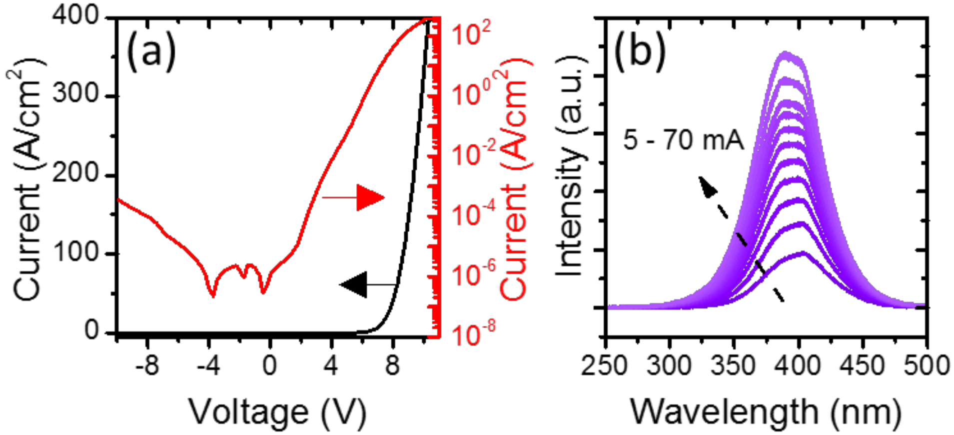


Nanowire LEDs on metal

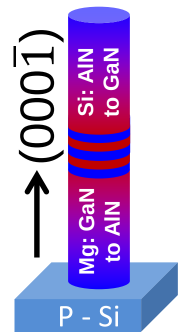




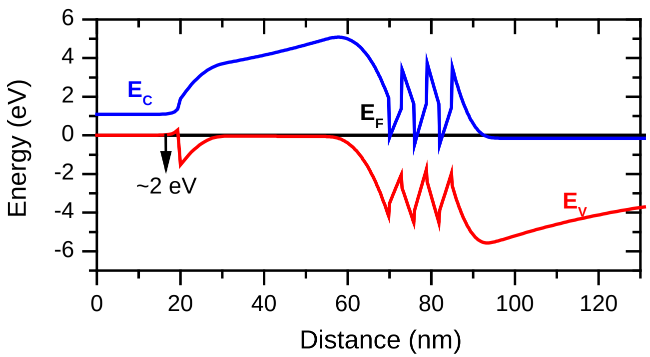




PINLEDs on p-Si



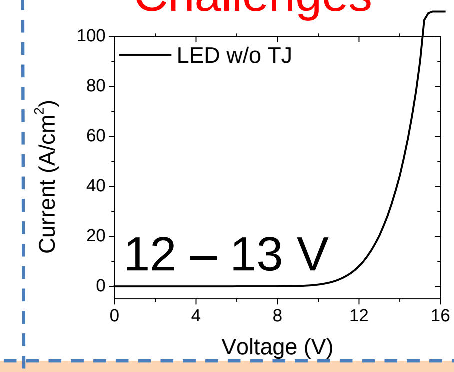
LED on P-Si

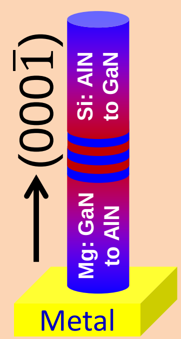


Attributes

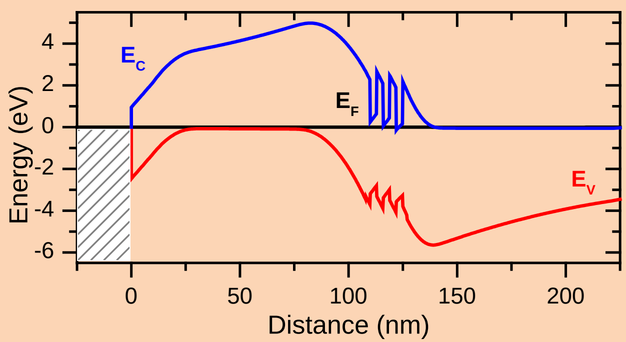
- Right orientation for polarization doping
- DUV emission

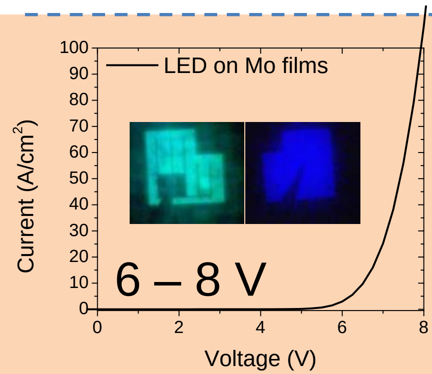
Challenges



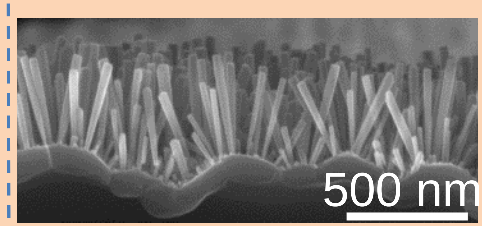


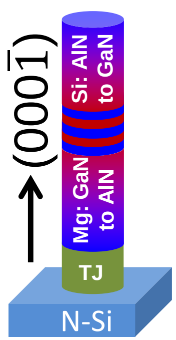
LED on Metal



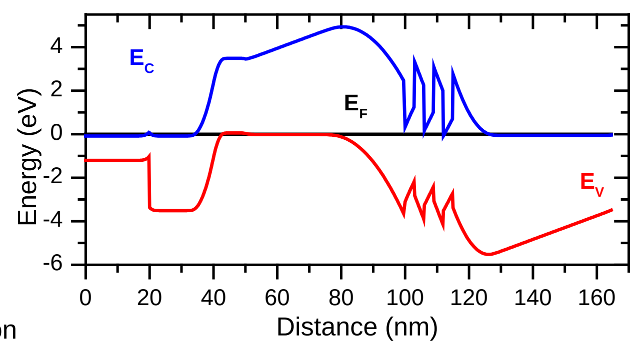


- Delamination of metal films

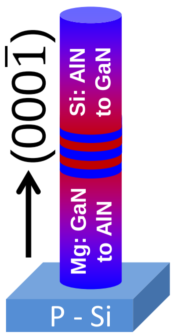




LED w Tunnel Junction



PINLEDs on p-Si



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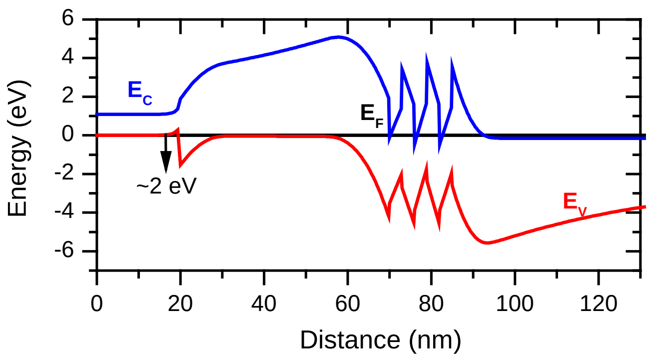
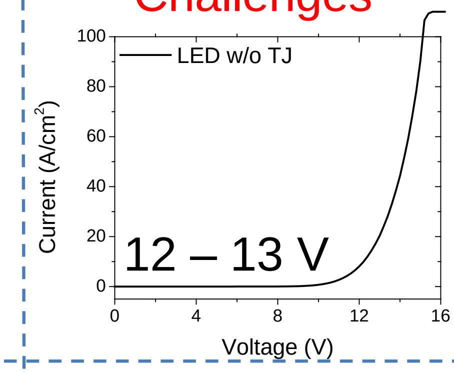
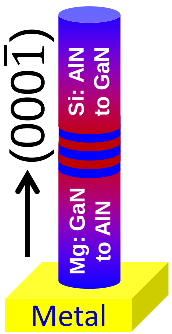


Attributes

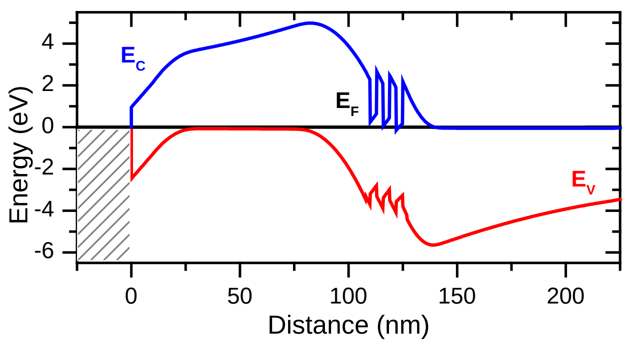
- Right orientation for polarization doping
- DUV emission

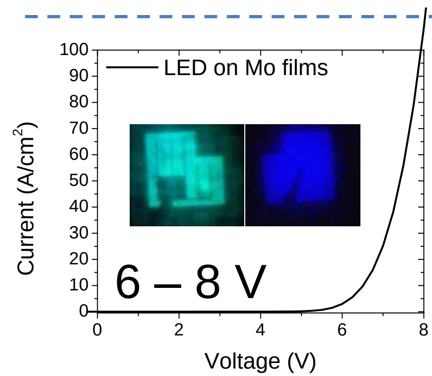
Challenges





LED on Metal





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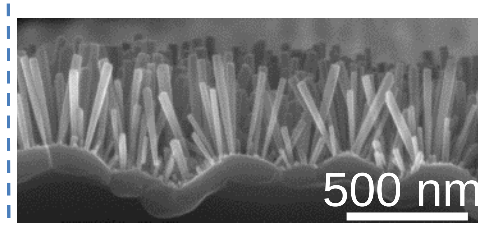
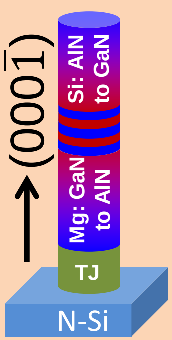
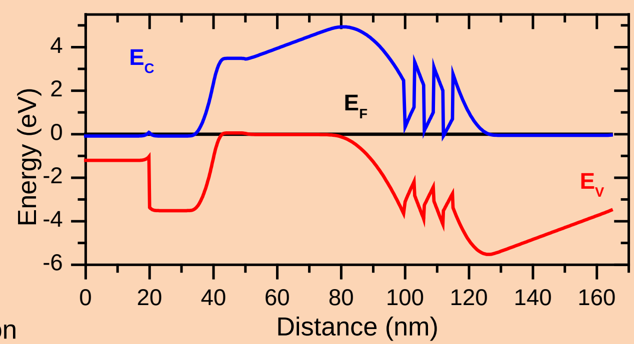
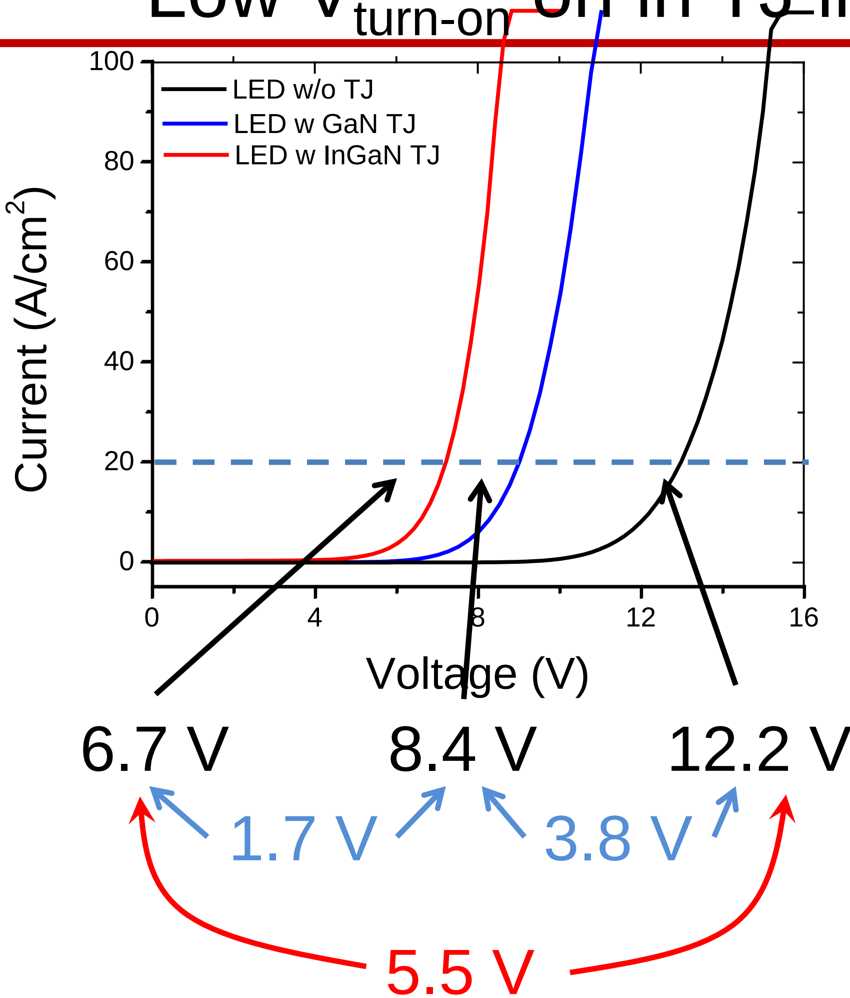


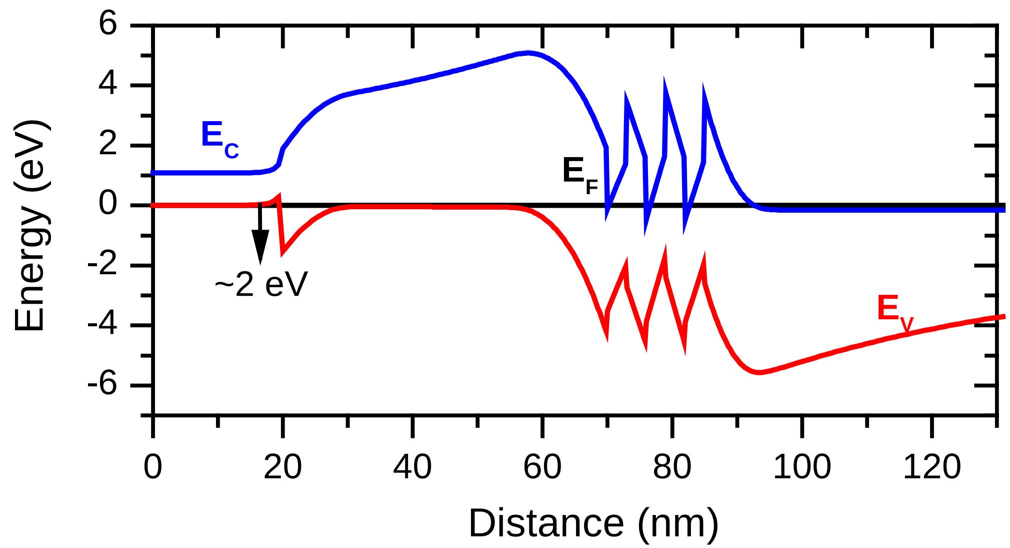


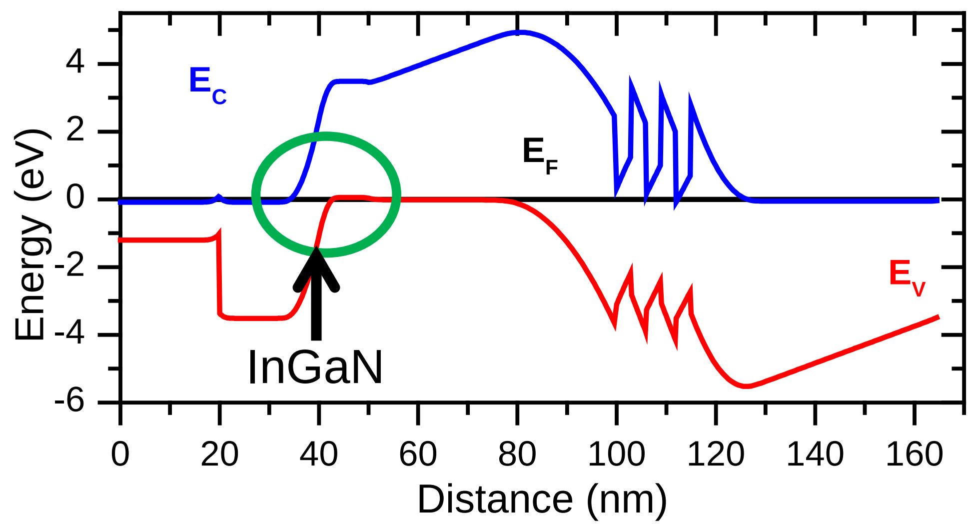
LED w Tunnel Junction



Low $V_{turn-on}$ in TJ integrated nanowire LEDs



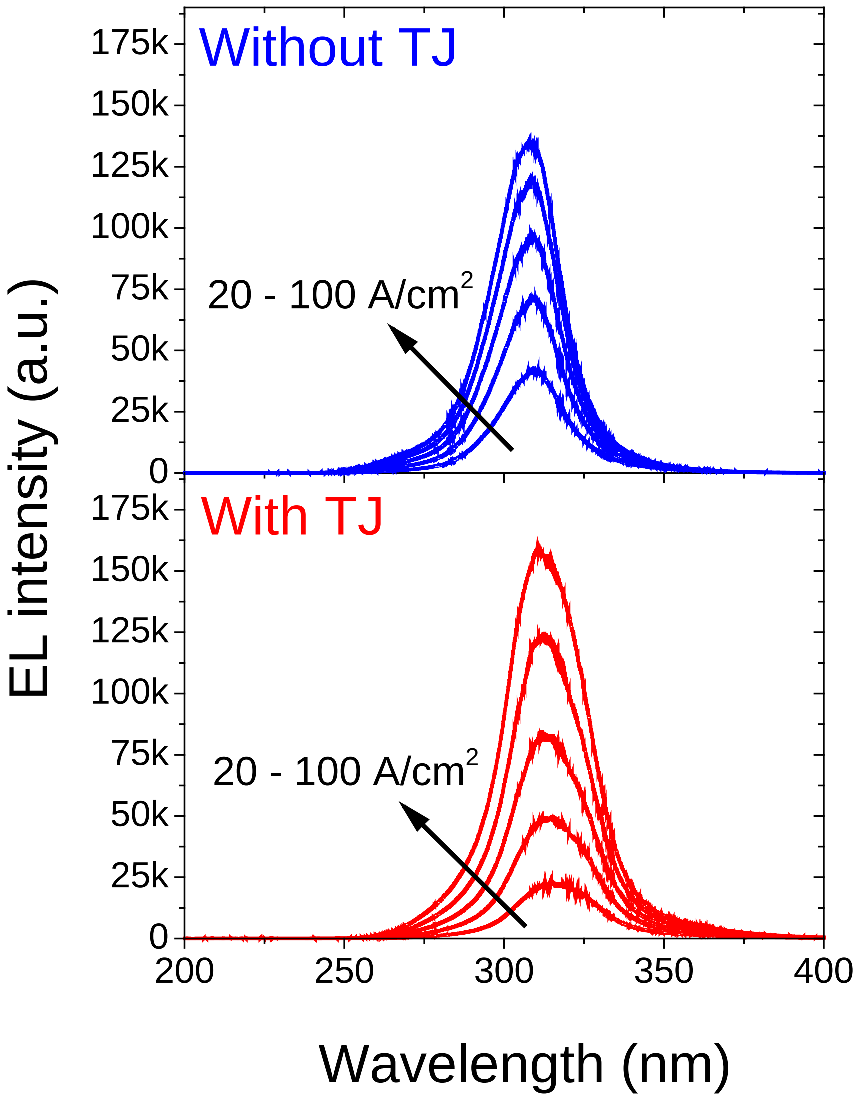


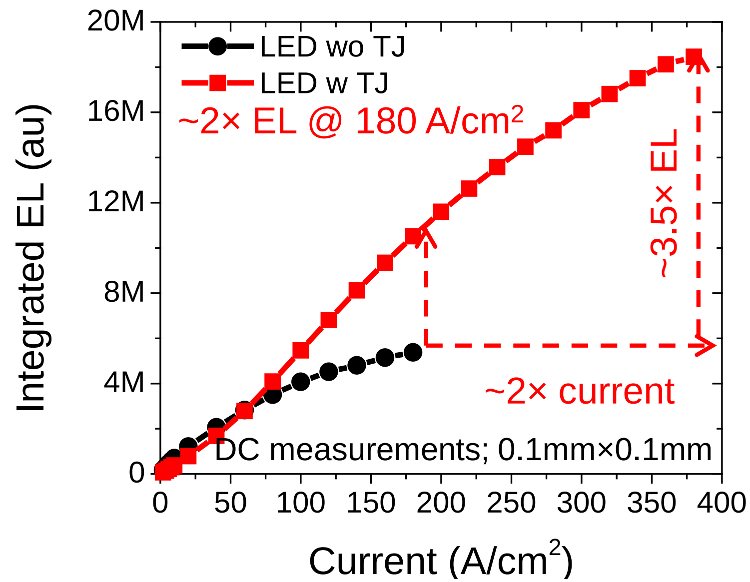


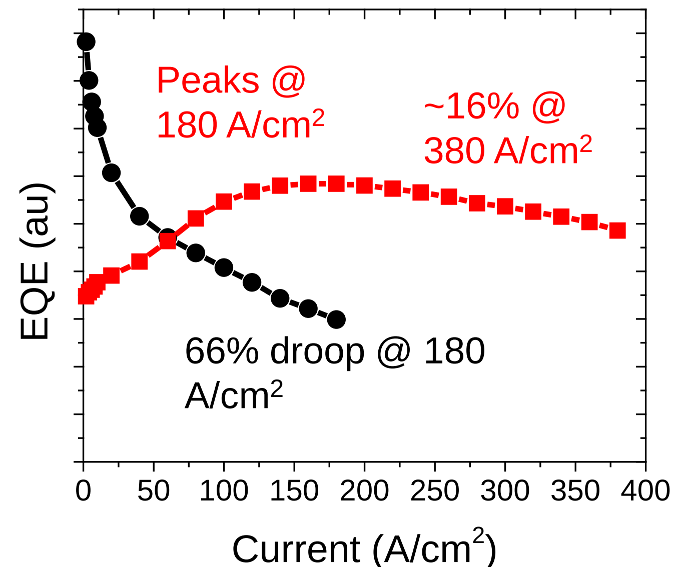
InGaN insertion

- Increases tunneling probablity
- Decreases t_{bar}
- Decreases $E_g(eff)$

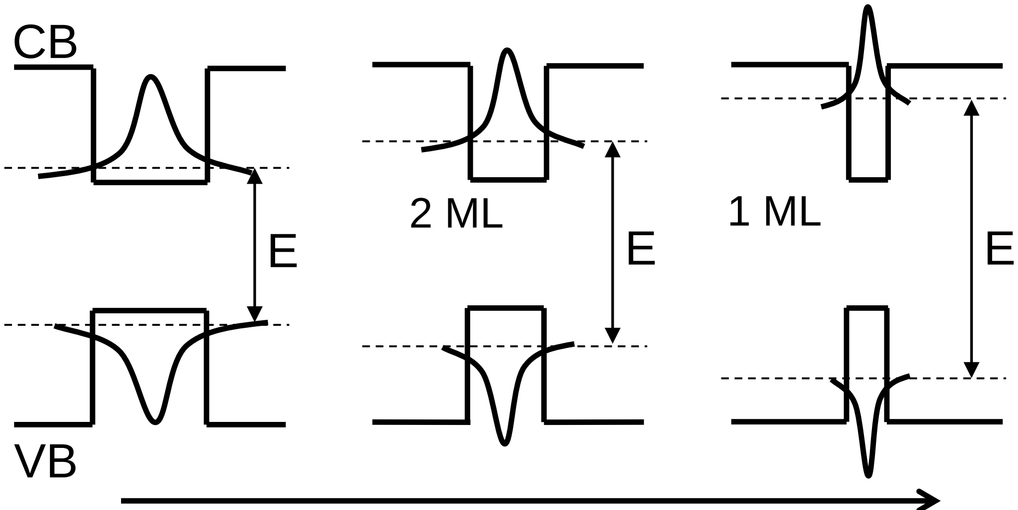
Suppressed efficiency droop in TJ integrated LEDs

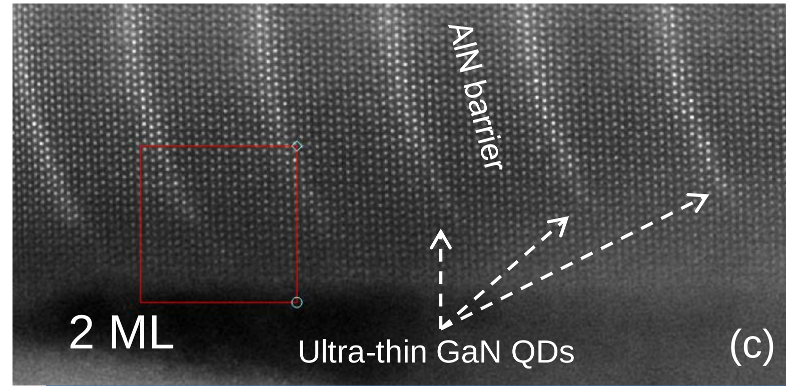


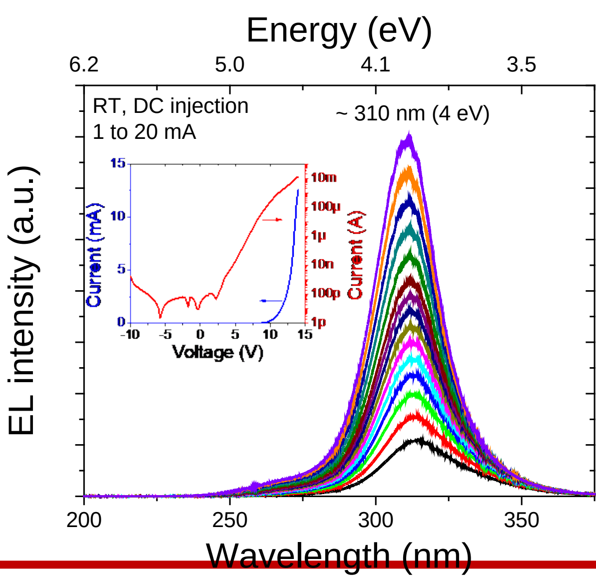


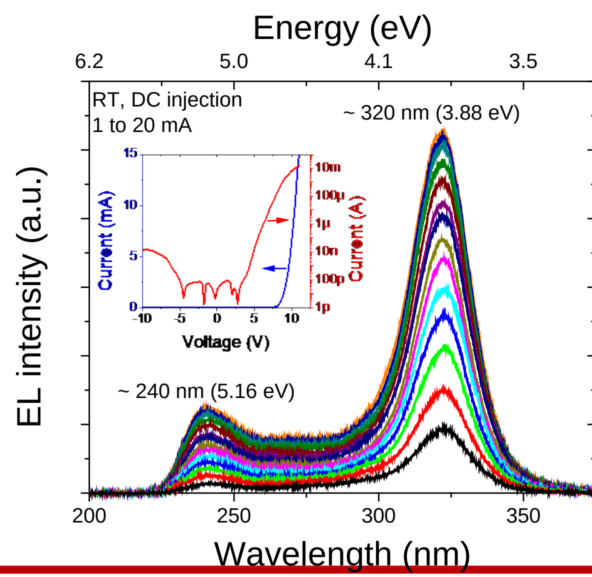


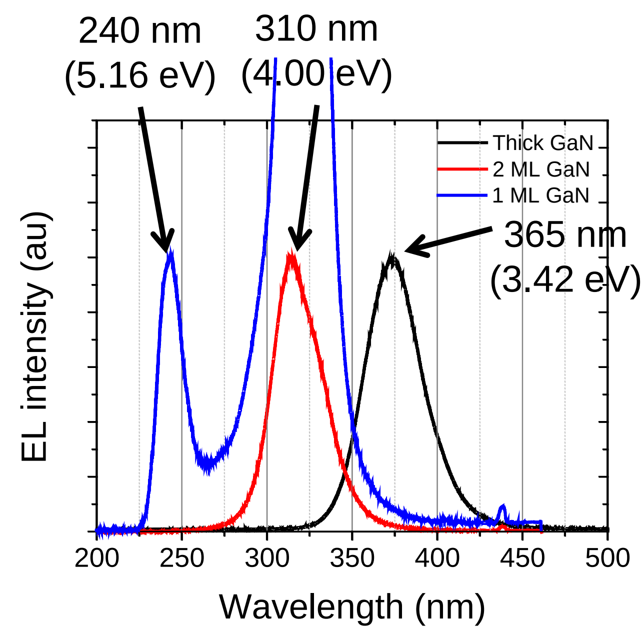
DUV emission utilizing extreme quantum confinement



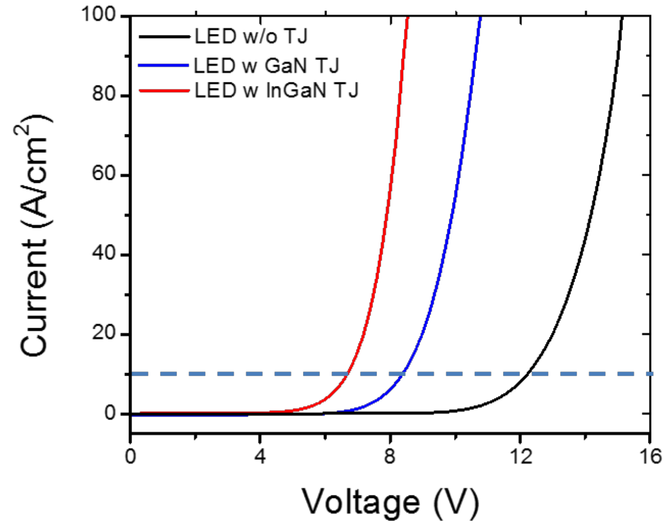


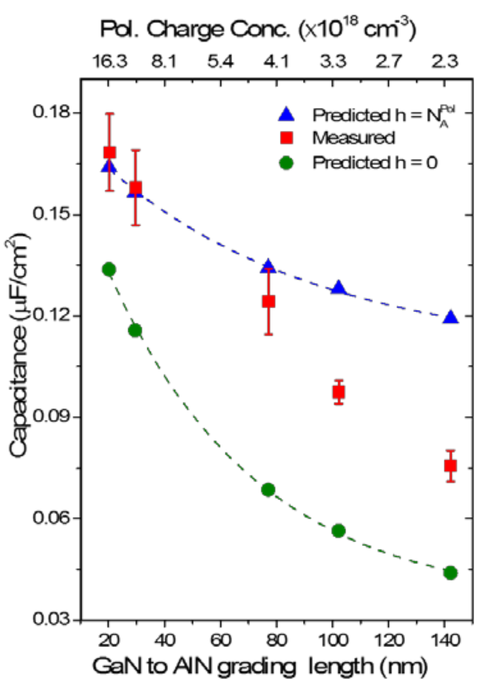


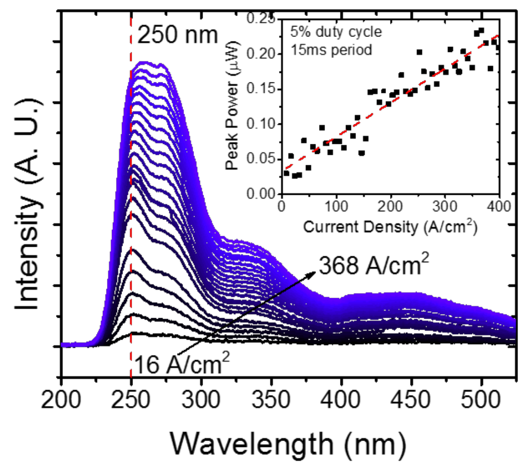


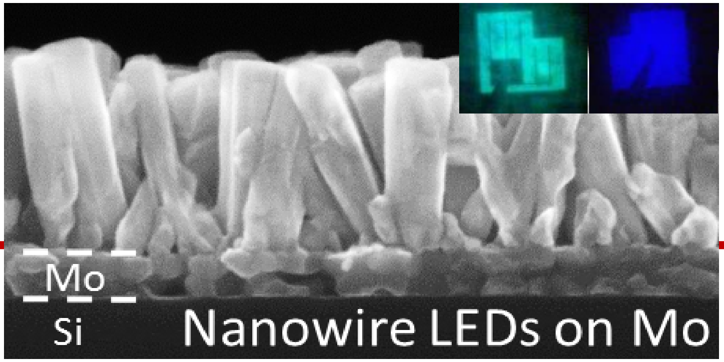


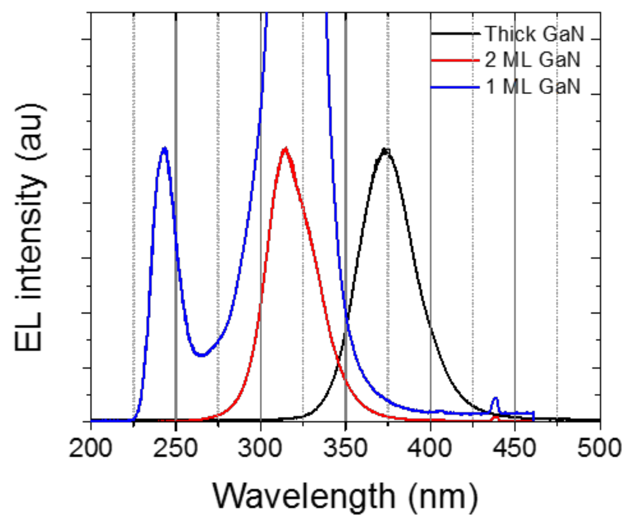
- Pol. hole doping in nanowires
- DUV emission from PINLEDs
- Nanowire LEDs on metal
- Tunnel junction int. PINLEDs
- DUV emission from GaN QDs











Ultraviolent Nanowire LEDs Grown Directly on Flexible Metal Foil: A Rout Toward Scalable Molecular Beam Epitaxy

B.J. May[1], A.T.M. G. Sarwar[2], J. Orsborn[1], H. L. Fraser[1], R.C. Myers[1,2]

[1]Department of Materials and Science Engineering, The Ohio State University
[2]Department of Electrical and Computer Engineering, The Ohio State University

Outline:

Background on nanowire LEDs

GaN nanowire LED on metal thin film

GaN nanowires on bulk metal foil

The first UV LED on metal foil

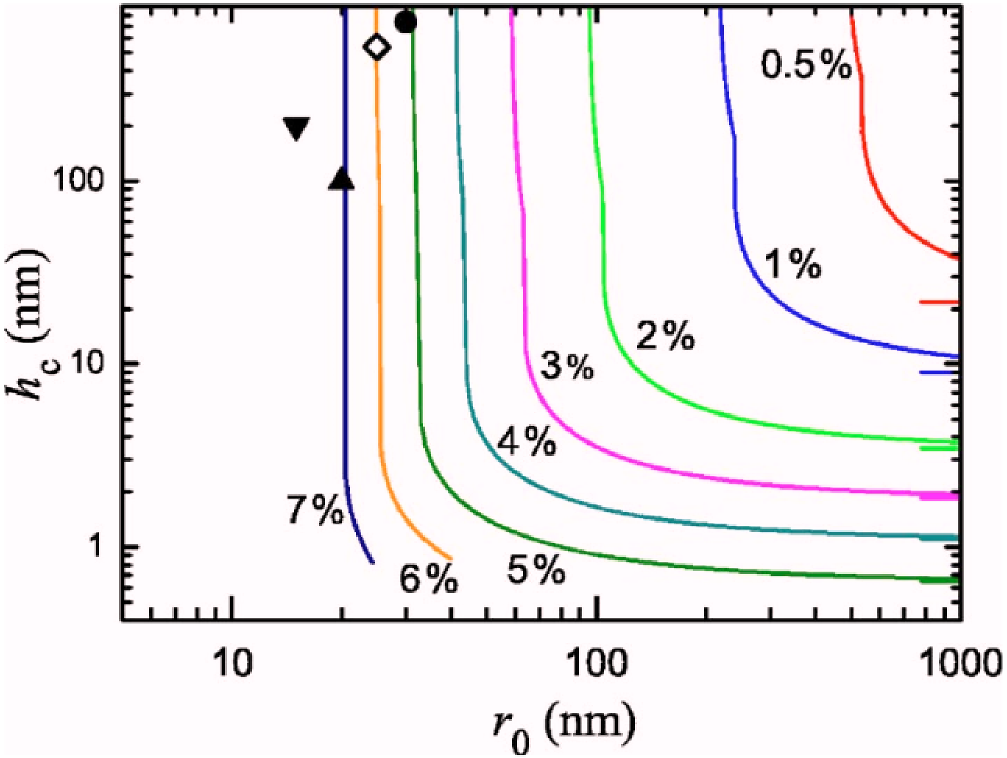
Advantages of Nanowires

<u>Advantages of nanowire photonics:</u>

- Lattice mismatch tolerance
- Zero threading dislocations
- Larger band gap and polarization tunability
- High optical quality on large variety of substrates

<u>Barriers to nanowire photonics</u>

- Nonuniformities → lower device efficiency

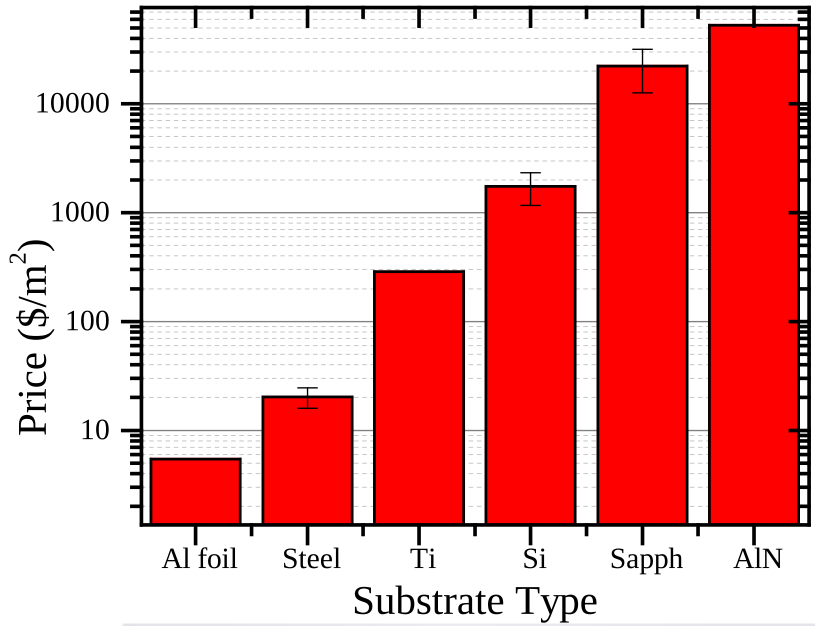


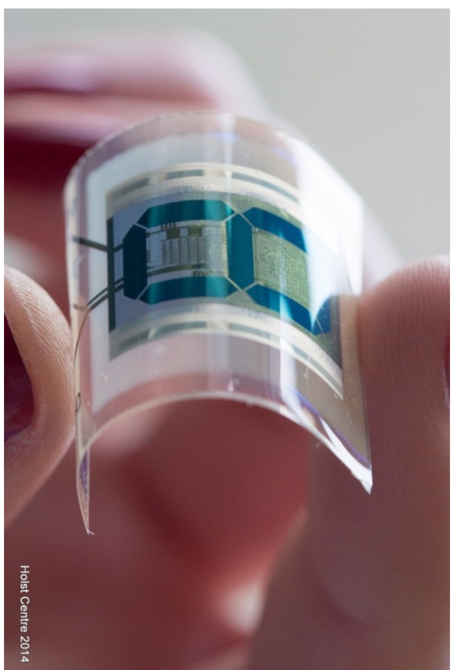
Glas, *PRB* 74, 121302 (2006)

Strategy → Use cheaper substrates than thin film photonics.

Scalability of Nanowire Photonics

- Thin film UV devices η ≈ 3%
  - grown on sapphire or AlN
- Nanowire UV devices η ≈ .003%
  - grown on Si substrates

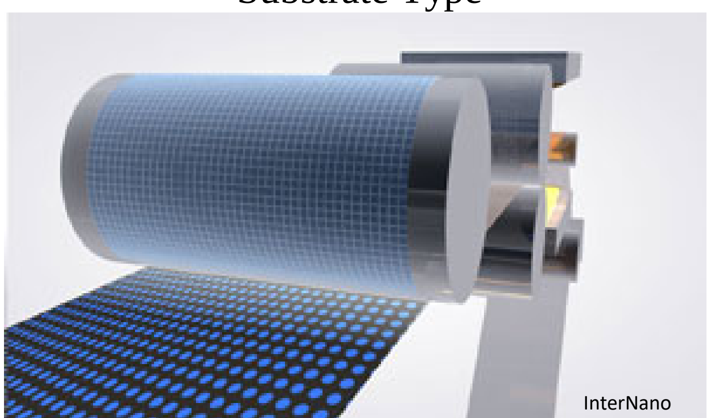




electroiq.com

<u>Why use metals?</u>

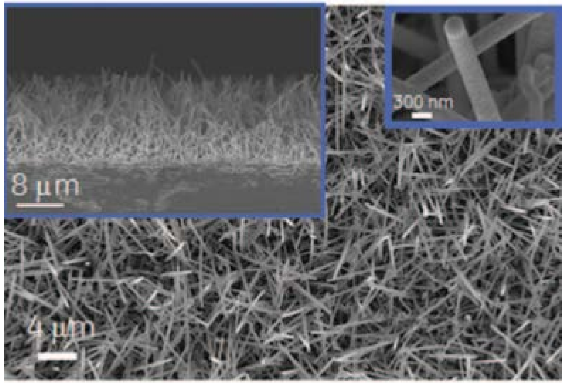
- Substrate cost
- Flexible optoelectronics
- Roll-to-roll manufacturing
- Growth on reflective materials
- There are certain electrical advantages



InterNano.org

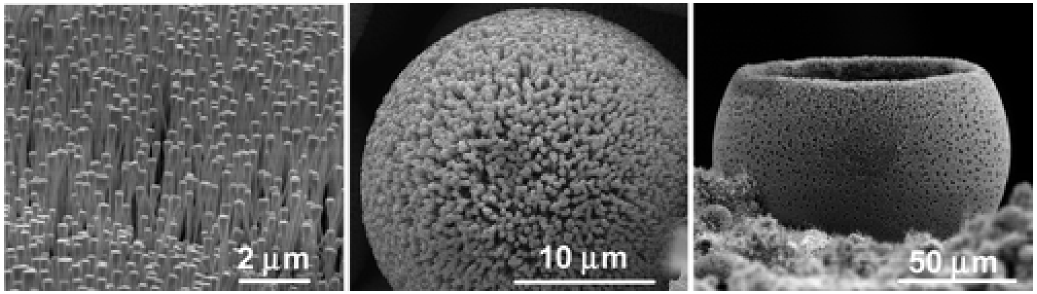
Nanowires on metals

Si nanowire photovoltaics on metal foil



Tsakalakos et al., *APL* (2007)

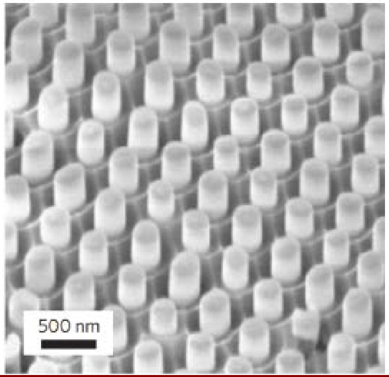
ZnO nanorods on Zn foils and spheres



→ broad green PL

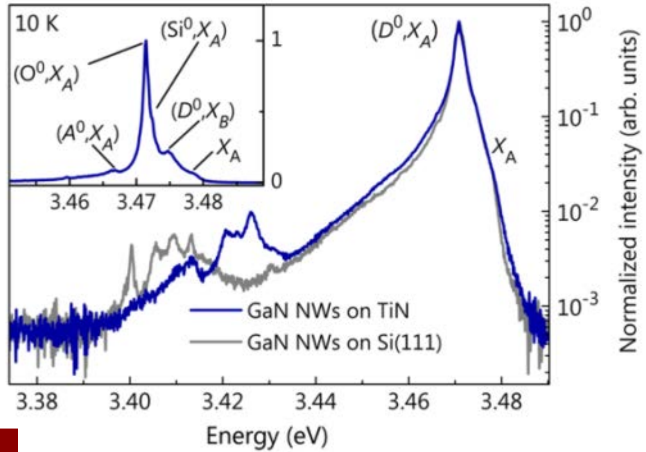
Gu et al., *ACS Nano* (2009)

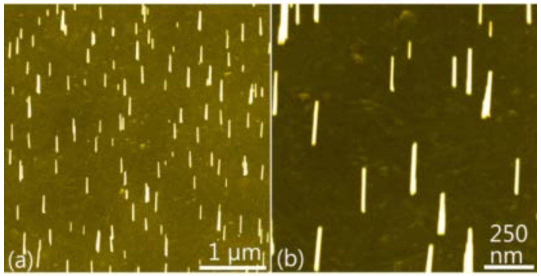
CdS nanopillar photovoltaics on aluminum foil



Fan et al., *Nature Materials* (2009)

Growth of GaN nanowires on TiN film





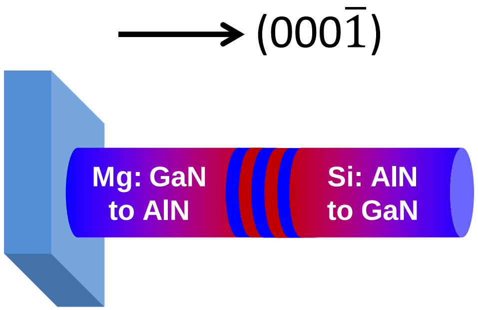
Wölz et al., *Nano Lett.* (2015)

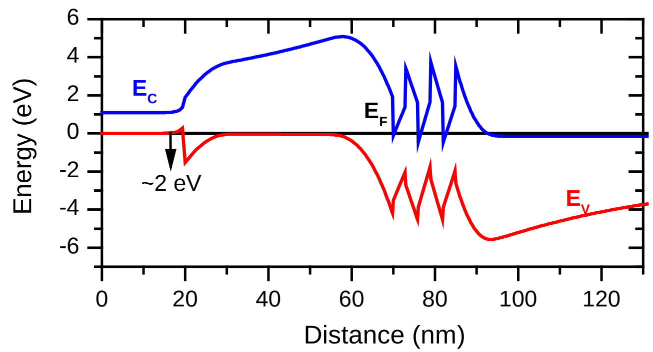
→ Near UV band edge PL (at 10 K)

→ Note: TiN is a ceramic

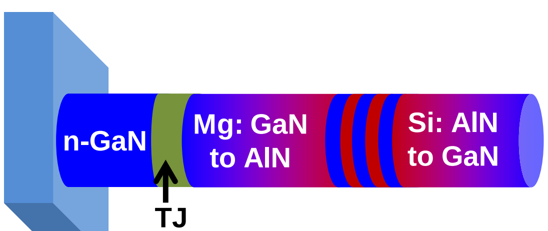
Polarization Induced Nano LEDs

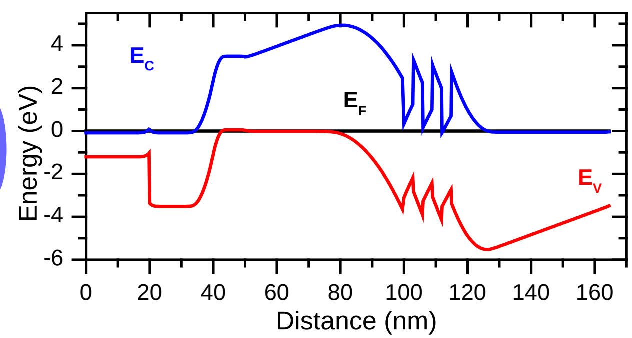
LED on p-Si



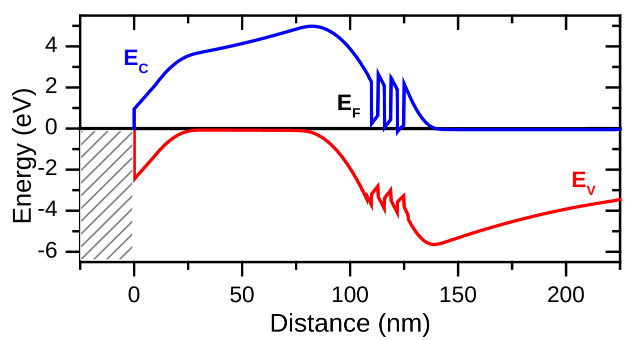


LED on n-Si





LED on Mo



- LED on p-Si has ~2eV valence band offset

Carnevale et. al., *Nano Lett.* 13, 3029 (2013)

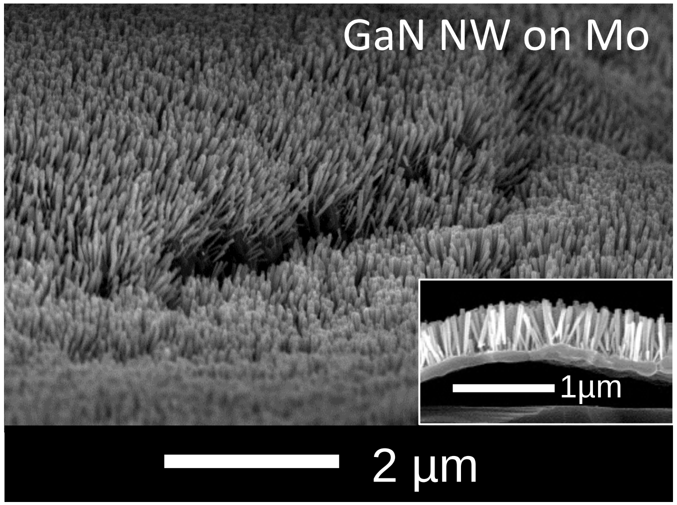
- Get rid of this by growth on n-Si with tunnel junction

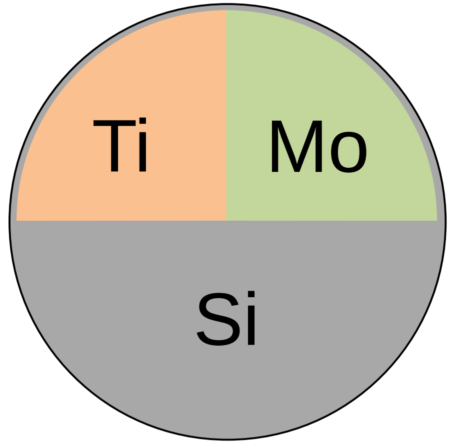
Sarwar et. al., *APL* 107, 101103 (2015)

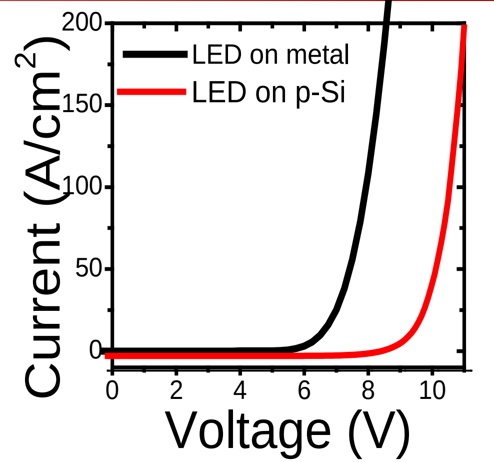
- Other option is to grow on high ϕ metal
  - Higher ϕ = removal of barrier

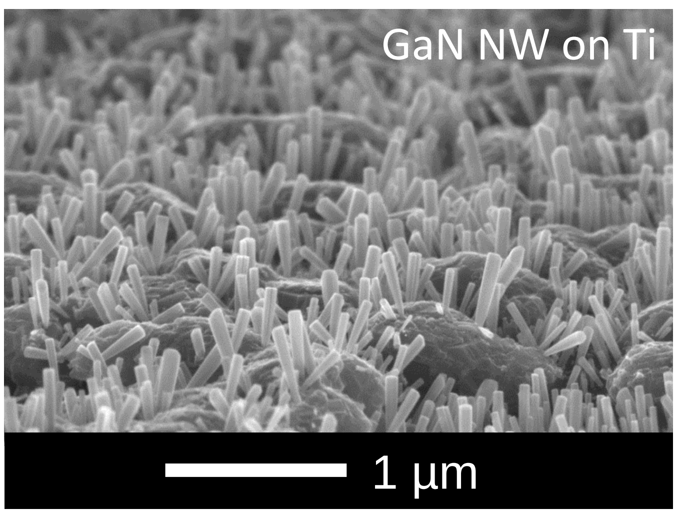
Sarwar et. al. *Small* 11, 5402-5408 (2015)

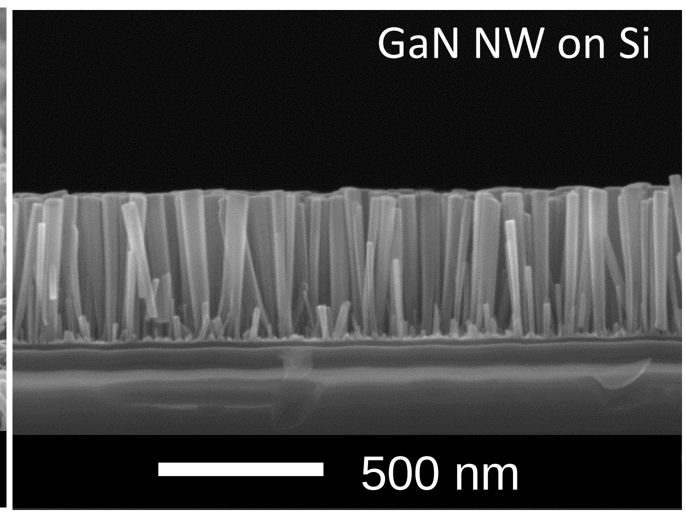
LED on Metal Film

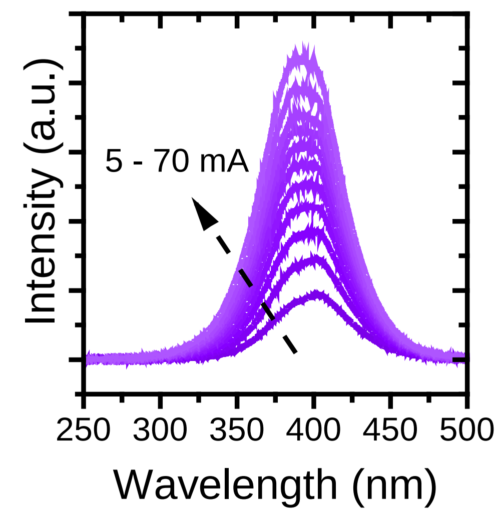










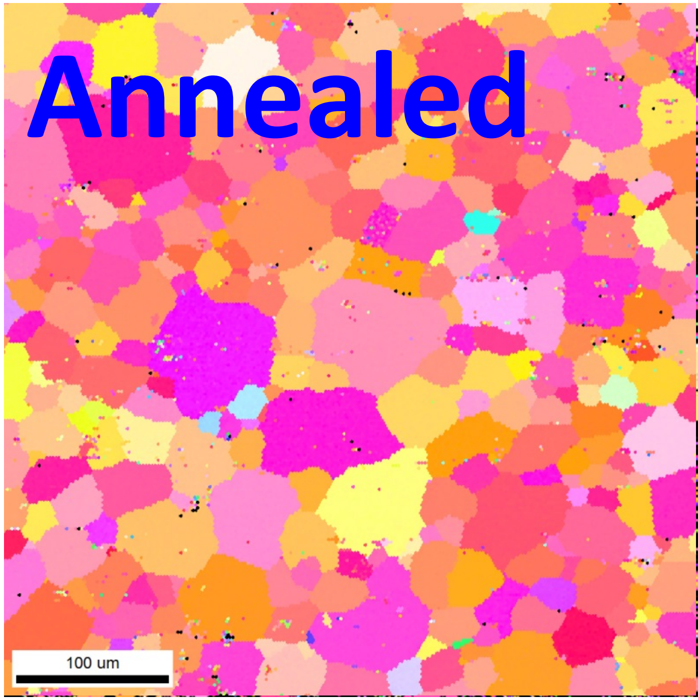


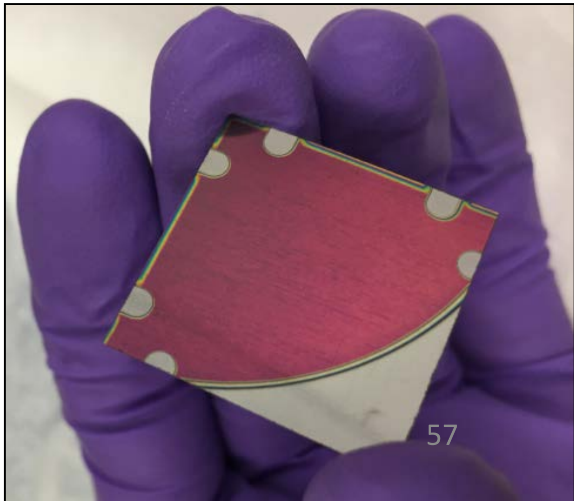
Sarwar et al., *Small* 11, 5402–5408 (2015)

GaN Nanowires on Metal Foils

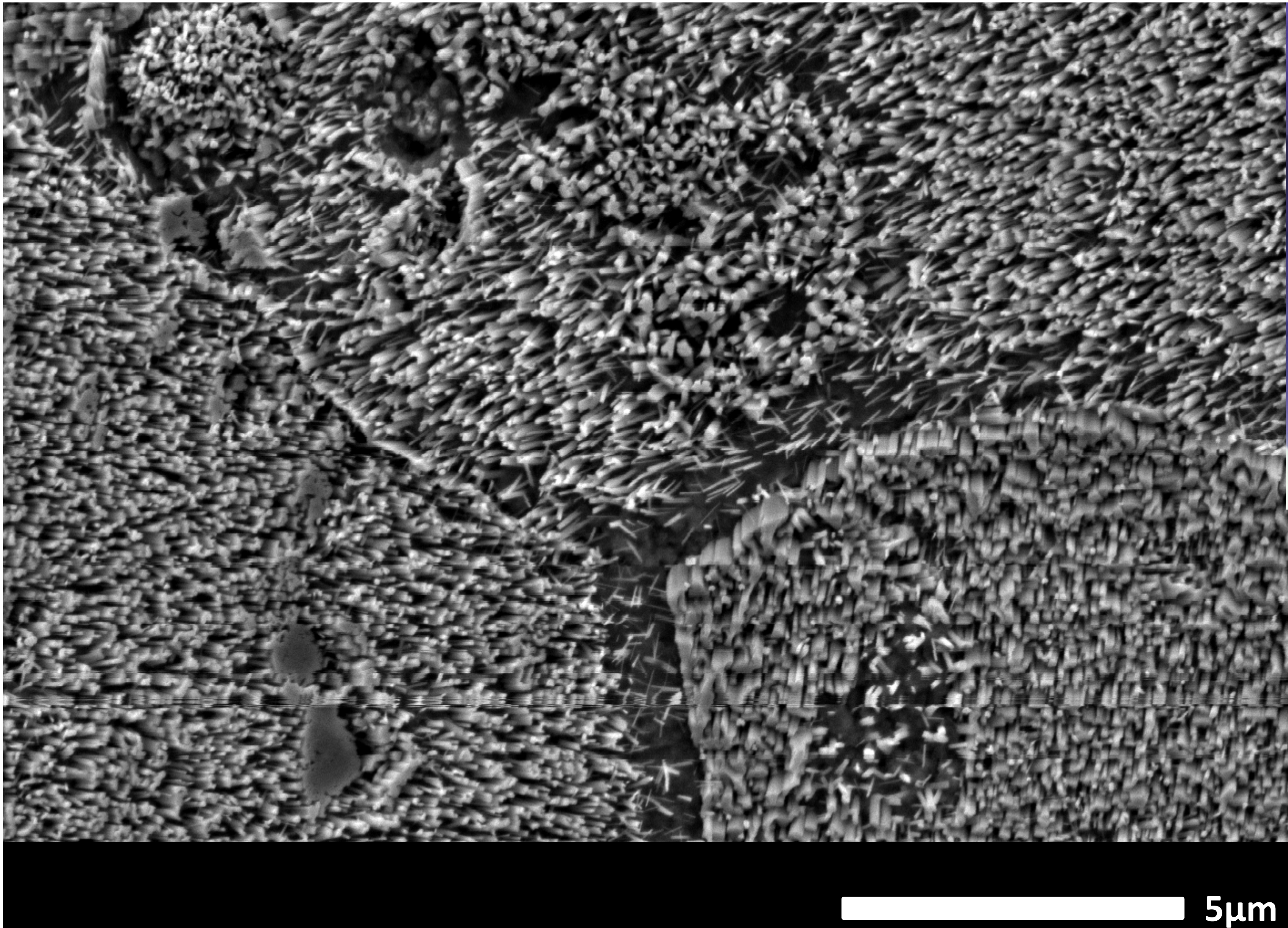
- Ti foil
  - 99.6% pure, 100µm thick
- Ta foil
  - 99.9% pure, 100µm thick
- Standard solvent cleaning
- Vacuum bake 600˚C before growth
- Use MBE 2 step growth
  - Nucleation at 750˚C for 5 minutes
  - Growth at 800˚C for 2 hours

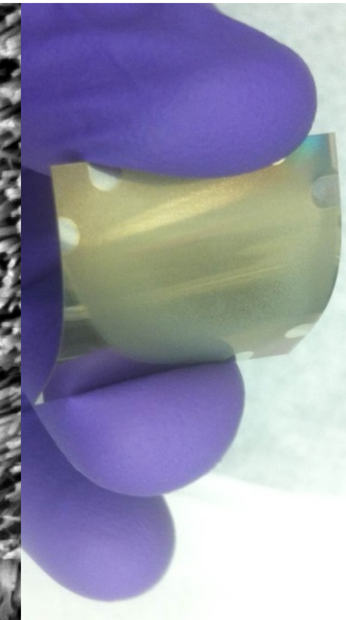
Carnevale, et. al., *Nano Lett.*, 11, 866 (2011)





GaN Nanowires on a Ti foil

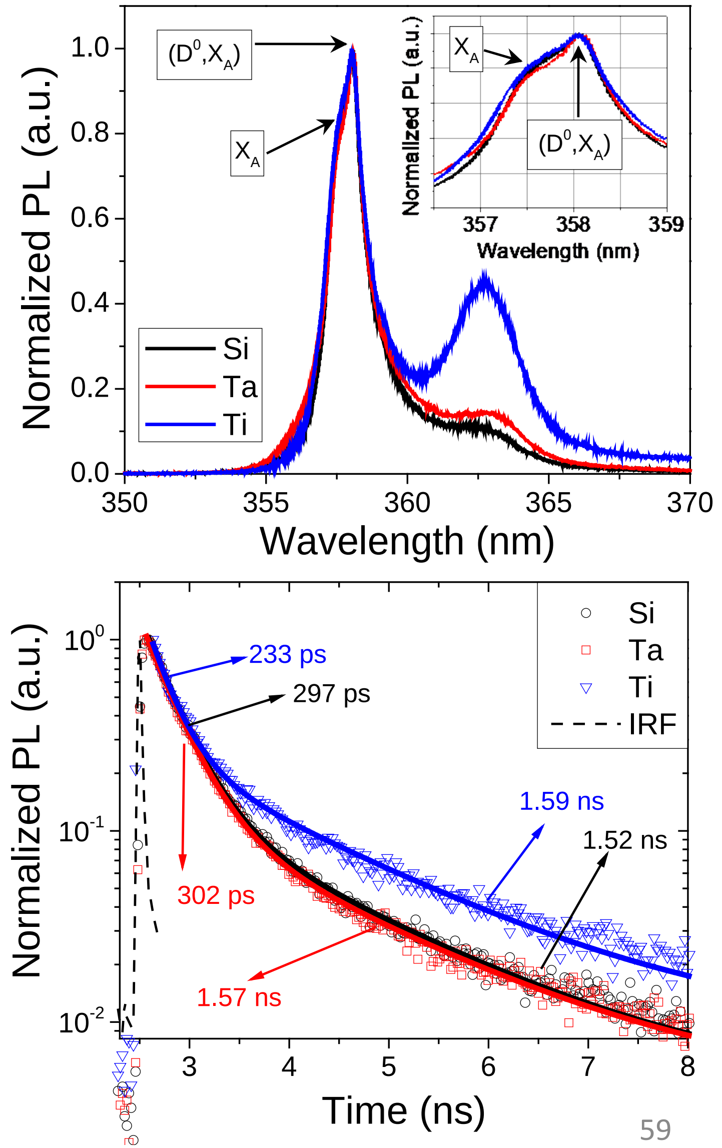




Brelon May - may.528@osu.edu NAMBE 2016

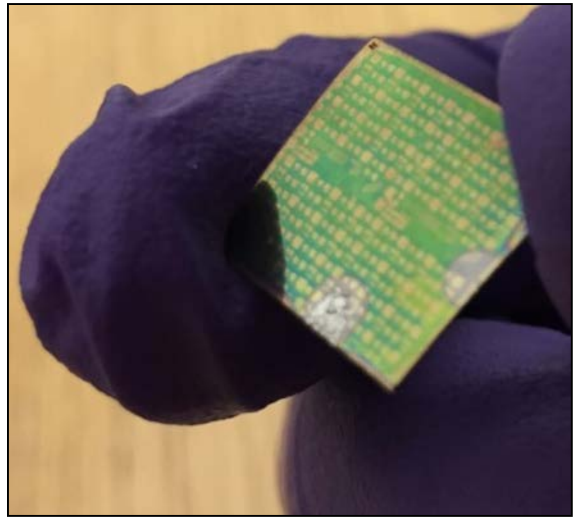
Optical Quality of Nanowires on Foils

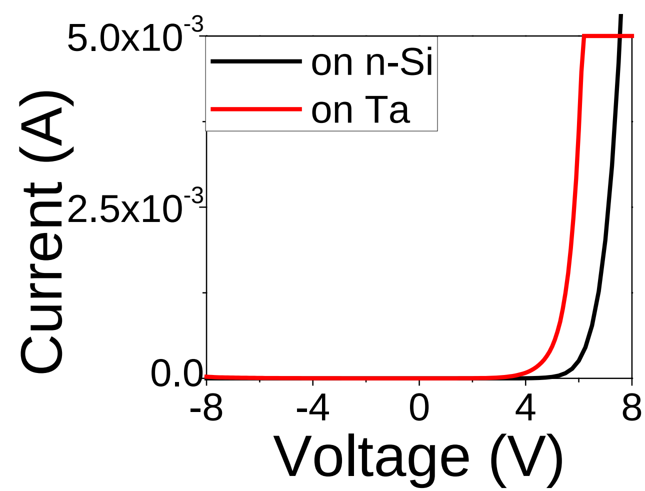
- Verification of optical quality with PL at 27K
- Foil samples were comparable to Si
  - No yellow defect luminescence
  - 363 nm peak from nanowire coalescence
- Time Resolved PL on the (D^0,X_A) peak also shows little difference from Si

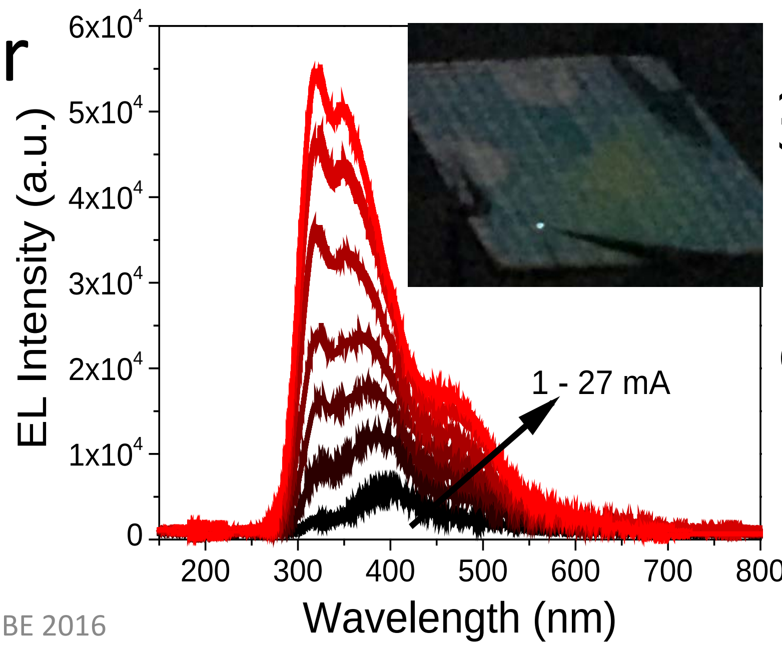


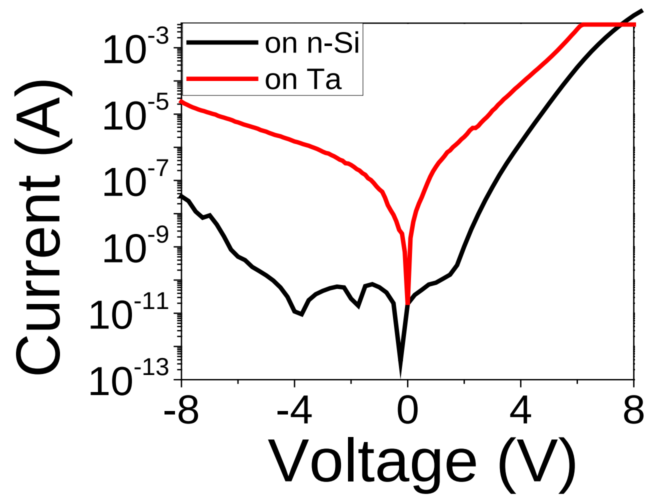
Operational Nano LEDs on metal foil

- Fabricated LED on Ta foil
- 10/20nm Ti/Au top contacts
- ~1V lower V_{th}
- 1000x higher leakage
- EL emission ~350nm





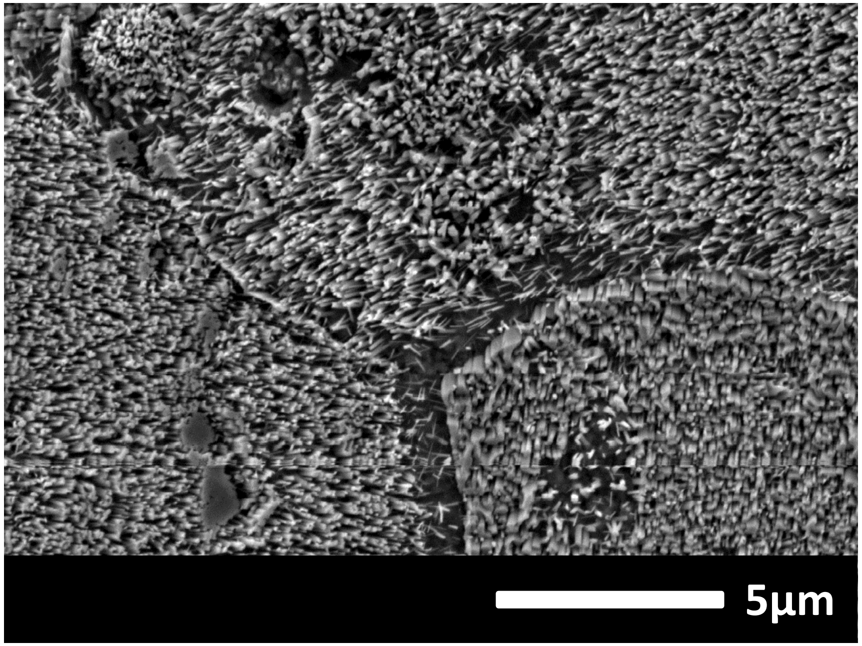


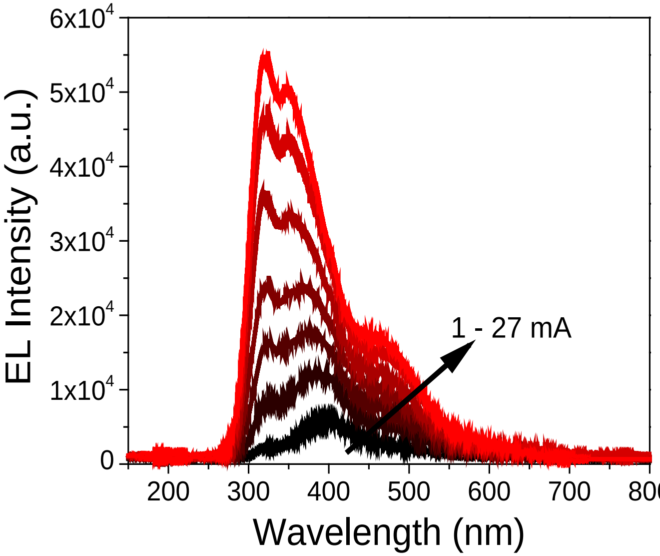


May, et. al., *APL* 108, 141103 *(2016)*

Summary and Conclusions

- High quality nitride nanowires were grown on flexible metal foils
- The first nitride LED was grown on a flexible foil
- Opens the door to roll-to-roll manufacturing of solid state optoelectronics





Funding provided by: